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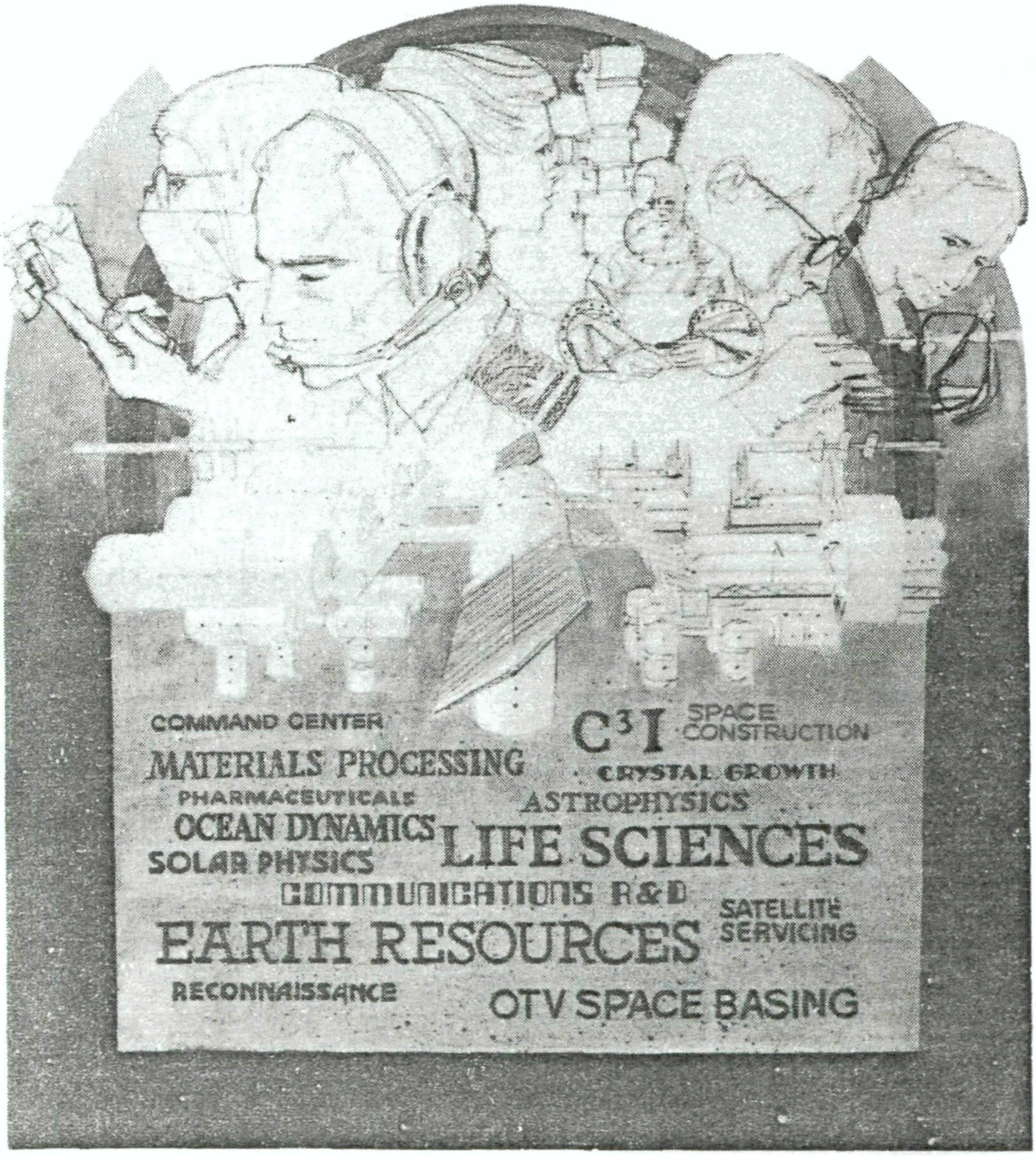
A STUDY OF SPACE STATION NEEDS, ATTRIBUTES & ARCHITECTURAL CONCEPTS

N84-27806

FINAL REPORT

VOLUME II • TECHNICAL

BOOK 2 • MISSION IMPLEMENTATION CONCEPTS



GENERAL DYNAMICS
Convair Division

:PORT NO. GDC-ASP-83-003
CONTRACT NO. NASW-3682

A STUDY OF SPACE STATION NEEDS, ATTRIBUTES & ARCHITECTURAL CONCEPTS

FINAL REPORT

VOLUME II • TECHNICAL
BOOK 2 • MISSION IMPLEMENTATION CONCEPTS

22 April 1983

Submitted to
National Aeronautics and Space Administration
Washington, D.C. 20546

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A STUDY OF SPACE STATION NEEDS, ATTRIBUTES AND ARCHITECTURAL OPTIONS

FINAL REPORT

VOLUME I	Executive Summary
VOLUME II	Technical Report
Book 1	Mission Requirements
Appendix I	Mission Requirements Data Base
Appendix II	Space Station User Brochure and Fact Sheet
Book 2	Mission Implementation Concepts
Book 3	Economic Benefits, Costs and Programmatics
Appendix I	Space Station Prospectus
Book 4	National Security Missions and Analysis

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PREFACE

The U.S. progress towards a complete space transportation system (STS) for the exploration and exploitation of space achieved an important milestone when the Space Shuttle became operational. Other elements of the system, such as the Payload Assist Modules, Inertial upper Stage, Spacelab, Extra Vehicular Maneuvering System, and the Shuttle-Centaur Upper Stage are either in use or under development. However, there are other important STS elements that still require definition and development -- the major new element being a manned Space Station in low earth orbit. When available, a manned Space Station, plus the elements listed above, will provide the capability for a permanent manned presence in space.

The availability of a manned Space Station will:

a Provide a versatile space system for an active space science program.

b. Stimulate development of advanced technologies.

c. Provide continuity to the civilian space program.

d. Stimulate commercial activities in space.

e. Enhance national security.

Through these, U.S. leadership in space will be maintained and our image abroad will be enhanced. The Space Station will provide:

a. A permanent manned presence.

b. Improved upper stage operations.

c. Maintenance of space systems through on-orbit checkout and repair.

d. Assembly and construction of large space elements.

It will also enhance Space Shuttle utilization as a transportation vehicle by releasing it from sortie missions that currently substitute for Space Station missions.

The Space Station will be a facility having the following general characteristics:

a. Support manned and unmanned elements.

b. User friendly.

c. Evolutionary in nature for size, capability, and technology.

h. High level of autonomous operations.

e. Shuttle compatible.

The primary purpose of this study was to further identify, collect, and analyze the science, applications, commercial, technology, U.S. national security, and space operations missions that require or that will be materially benefited by the availability of a permanent manned Space Station and to identify and characterize the Space Station attributes and capabilities that will be necessary to satisfy those mission requirements.

NASA intends to integrate these data, recommendations, and insights developed under this contracted effort with those developed from in-house activities and other sources and then synthesize from this information a set of mission objectives and corresponding Space Station requirements that will be used in future phases of study and Space Station definition.

The study objectives as defined in the Request or Proposal (RFP) are:

a. Identify, collect, and analyze missions that require, or will materially benefit from, the availability of a Space Station:

   - Science
   - Applications
   - Commercial
   - Technology
   - Space operations
   - U.S. national security

b. Identify and characterize the Space Station attributes and capabilities that are necessary to meet these requirements.

c. Recommend mission implementation approaches and architectural options.

d. Recommend time phasing of implementation concepts.

e. Define the rough order of magnitude programmatic/cost implications.

Book 1 will address the first objective and provide the realistic, time-phased set of mission requirements upon which the balance of the study was based. Accomplishments of objectives b, c, and d are documented in Book 2, and objective e is addressed in Book 3. Book 4 contains a definition and an analysis of national security missions (classified).

FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA Headquarters under Contract Number NASW-3682.

The study was conducted from 20 August 1982 through 22 April 1983. A mid-term briefing was presented at NASA Headquarters on 17 November 1982; a final briefing was presented on 5 April 1983, also at NASA Headquarters.

The study was conducted within the Space Programs Organization at General Dynamics Convair Division, headed by W. F. Rector, III, Space Vice President and Program Director. D. E. Charhut, Director of Advanced Space Programs, was assigned specific responsibility for the study. The NASA COR is Brian Pritchard of the Space Station Task Force headed by John Hodge.

General Dynamics Convair Division personnel who significantly contributed to the study include:

Study Manager	Otto Steinbronn
Mission Requirements	Warren Hardy - Manager Jim Peterson Charlie Hyde
Mission Implementation	John Bodle - Manager Earl Davis Tom Kessler Johna Hanson
Cost and Programmatics	Bob Bradley - Manager Michael Simon Sam Wagner
National Security Missions	Al Phillips Clint James

Subcontract support was obtained from Space Communications Co. (SPACECOM) in the area of communication spacecraft and related technologies, and from Advanced Technology, Inc. in the area of life science and life support systems.

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ABBREVIATIONS AND ACRONYMS

ACS	Attitude Control System
AMCD	Annular Momentum Control Device
APU	Auxiliary Power Unit
ATP	Authorization to Proceed
ATVCA	Attitude, Translation and Velocity Control Assembly
CCAFS	Cape Canaveral Air Force Station
CCD	Charged Coupled Device
CELSS	Closed Ecology Life Support System
C&TS	Communications and Tracking Subsystem
CITE	Cargo Integration Test Equipment
CMOS	Complementary Metal Oxide Silicon
CSA	Construction System Assembly
CTP	Communications and Tracking System Processor
DACS	Data Aquisition and Control System
dBW	Decibels (referenced to one watt)
deg	Degree
DME	Distance Measuring Equipment
DOD	Department of Defense
DRIRU	Dual Redundant Inertial Reference Unit
EC/LSS	Environmental Control/Life Support System
ET	External Tank
EUS	Expendable Upper Stage
EVA	Extravehicular Activity
FF	Free-Flyer
FFS	Free-Flyer Servicing
FMDM	Flexible Multiplexer-Demultiplexer
GEO	Geostationary Earth Orbit
GLOW	Gross Lift-Off Weight
GPS	Global Positioning Satellite
HEO	High Earth Orbit
HLLV	Heavy Lift Launch Vehicle
I	Inclination
Isp	Specific Impulse
I/F	Interface
IOC	Initial Operating Capability
IR	Infrared
IRU	Inertial Reference Unit
IUS	Inertial Upper Stage
IVA	Intravehiclar Activity
JSC	Johnson Space Center
KBPS	Kilo-Bits Per Second
KSA	K-band Single Access
KSC	Kennedy Space Center
LED	Light Emitting Diode
LEO	Low Earth Orbit
LSS	Large Space Structure

ABBREVIATIONS AND ACRONYMS, Cont'd.

MA	Multiple Access
MACS	Modular Attitude Control System
MBPS	Mega-Bits Per Second
MPS	Mega-Bits per Second
MMS	Multimission Modular Spacecraft
MLP	Mobile Launcher Platform
MPS	Materials Processing Science
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NORAD	North American Air Defense Command
O&C	Operation and Checkout
O&M	Operation and Maintenance
O&S	Operations and Servicing
OPF	Orbiter Processing Facility
OTV	Orbital Transfer Vehicle
PN	Pseudo-Noise
PPF	Payload Processing Facility
R&D	Research and Development
RAM	Random Access Memory
RCS	Reaction Control System
RD&P	Research, Development and Production
RF	Radio Frequency
RMS	Remote Manipulation System
ROM	Rough Order of Magnitude
SBOTV	Space Based Orbital Transfer Vehicle
SCAFE	Space Construction Automated Fabrication Experiment
SDV	Shuttle Derived Vehicle
SIRCA	Stellar Inertial Reference Control Assembly
SLATS	Semiparabolic Low Aperture Trough Solar
SMAB	Solid Motor Assembly Building
SOFI	Spray-On Foam Insulation
SOS	Silicone-On-Sapphire
SRR	System Requirements Review
SSA	S-band Single Access
SSAF	S-band Single Access Forward
SSAR	S-band Single Access Return
SSME	Space Shuttle Main Engines
STACC	Standard Telemetry and Command Components
STDN	Space Tracking and Data Network
STS	Space Transportation System
TDAS	Tracking and Data Acquisition System
TDM	Technology Development Mission
TDRSS	Tracking and Data Relay Satellite System
TMS	Teleoperator Maneuvering System
VAB	Vertical Assembly Building
VAFB	Vandenberg Air Force Base
VPF	Vertical Processing Facility

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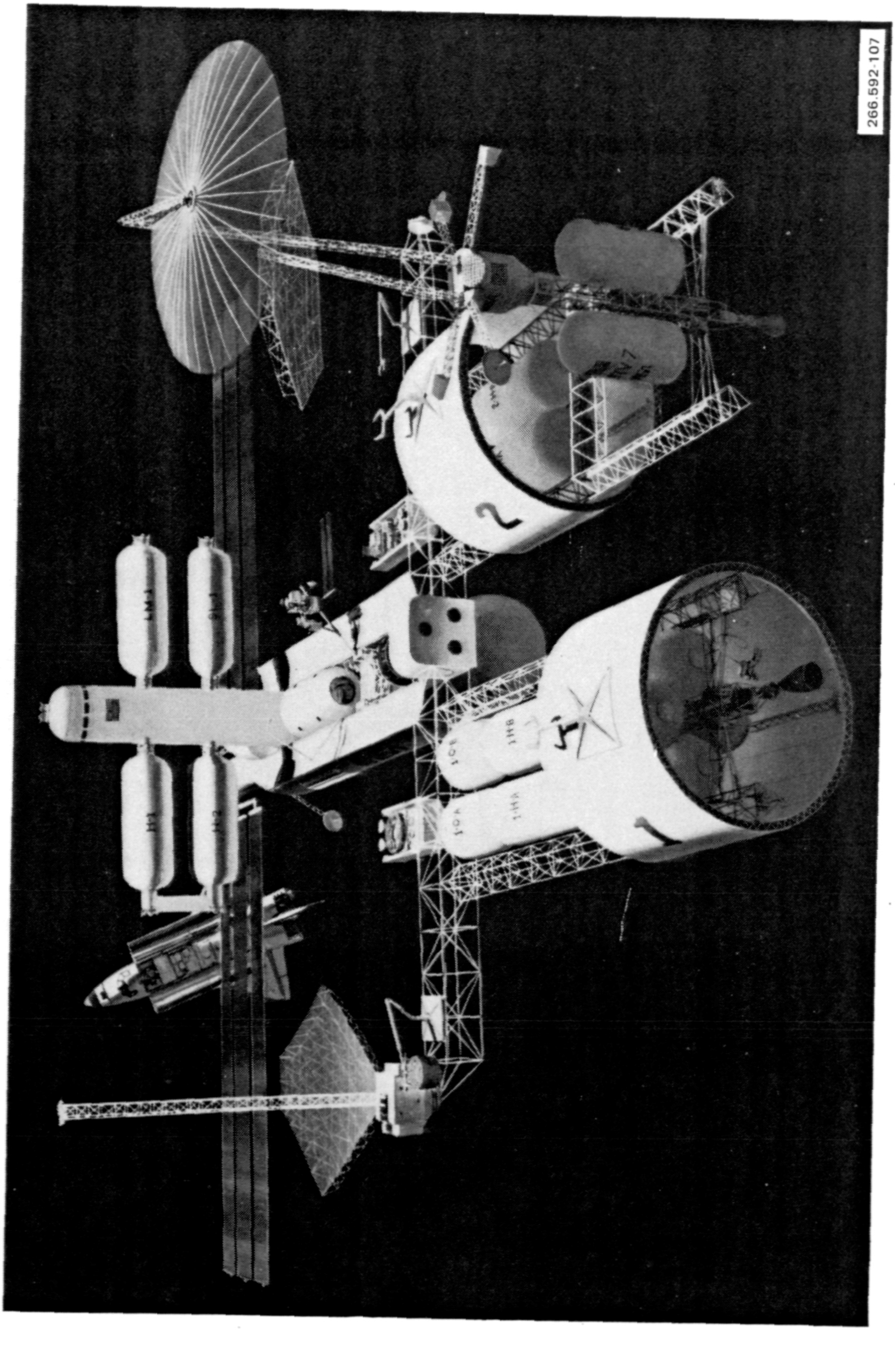
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SECTION 1

INTRODUCTION AND SUMMARY

1.1 SCOPE

This is the second of four books comprising the technical volume of the final report on A Study of Space Station Needs, Attributes and Architectural Options. It contains a summary of all study tasks performed in the area of defining Space Station system attributes and architectural concepts required to accommodate and implement the space missions identified in the years 1990 through 2000 as reported in Book 1 of this volume.

1.2 MISSIONS IMPLEMENTATION TASK OVERVIEW

1.2.1 OBJECTIVES. The top level objective of the Missions Implementation Concepts Task was to define a recommended Space Station System architectural and evolutionary concept and program options. Subordinate objectives included:

a. Define space systems, system element, and subsystems requirements.

b. Define architectural and evolutionary concepts for major space system elements and subsystem.

c. Define major space system element operations concepts and the role of man in accomplishing these operations.

d. Define space systems and subsystems technology needs.

e. Define space systems programmatic options and identifying evolving business opportunities and program strategies for a Space Station system (reported in Volume II, Book 3).

1.2.2 APPROACH. The Missions Implementation Task was divided into five major tasks as shown in Figures 1-1 and 1-2. Task 3.2.1 initially focuses on a thorough functional analysis which synthesized functional elements requirements into system and subsystem functional concepts that were used to define architectural options for the Space Station System. This effort was paced by the acquisition of missions requirements during the initial study phase.

Major subsystems requirements were defined to allow subsystems functional concepts to be developed and evaluated. A manned Space Station operational activities analysis was performed to establish preliminary requirements for crew size, crew tasks, crew timelines, crew equipment, automated elements and system arrangements, to support the definition of subsystems and system functional concepts. Selected concepts were used to identify technology needs and develop Space Station architectural concepts.

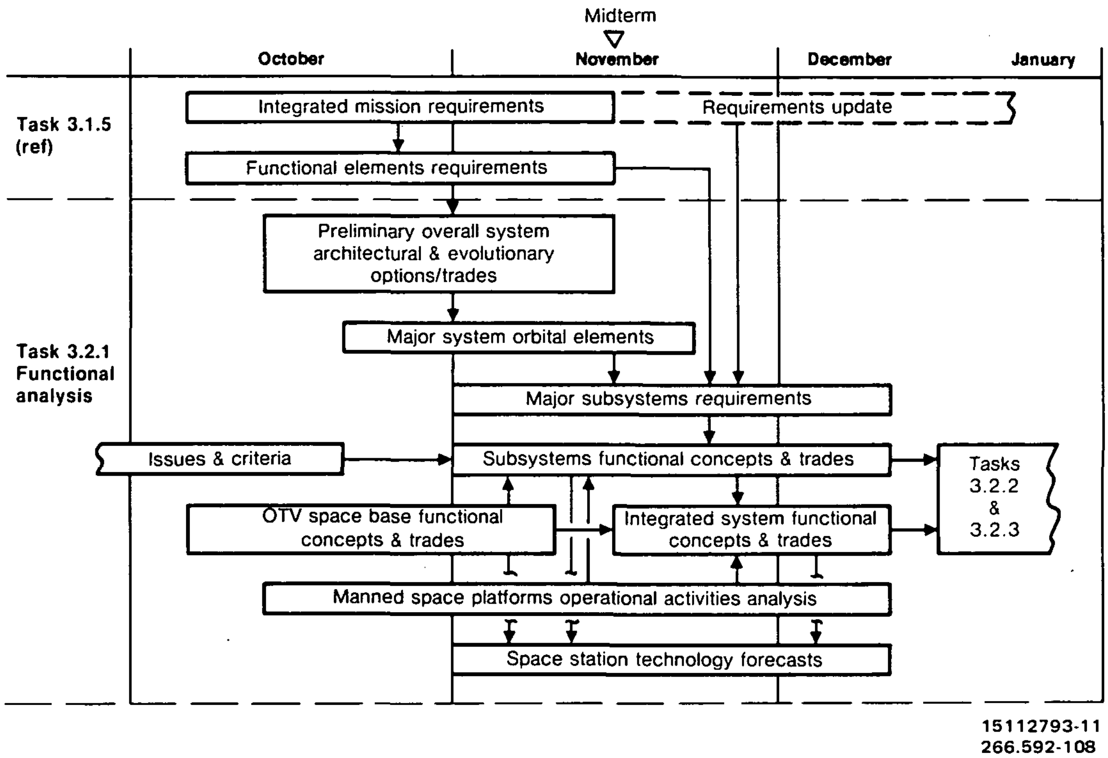

Figure 1-1. Initial Task

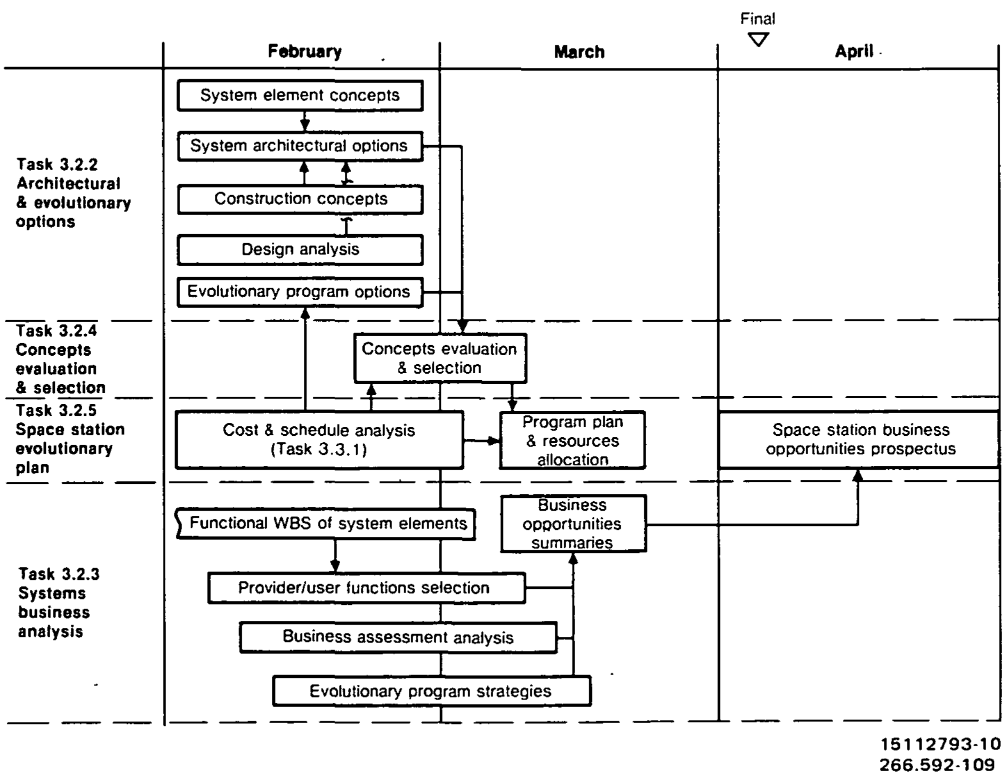

Figure 1-2. Final Task

The final missions implementation task included the definition of Space Station System architectural options, evaluation of these options, selection of a preferred option and development of a program plan and ROM program costs for the preferred option.

In addition, we performed a systems business analysis which identified the potential business opportunities available to industry, either as a provider of Space Station elements or as a user of Space Station elements.

For example, a provider function could include such elements as: (1) an Orbiter-Transfer-Vehicle (OTV); (2) a general purpose laboratory module; (3) a data processing system, etc. These functions would generate revenues which would give the provider a return on investment through several possible institutional arrangements between government and private industry. The systems business analysis created and evaluated institutional options as well as exploring other methods by which the government can encourage private development of Space Station functions. These analysis were used to formulate evolutionary program strategies driven by specific business opportunities. These opportunities were defined for prospective entrepreneurs and documented in our Space Station Opportunities Prospectus, which is provided as an addendum to this Final Report (see Book 3, Appendix I).

1.3 MISSIONS IMPLEMENTATION TASK SUMMARY

The results of the Missions Implementation Task are summarized as follows:

a. Functional analysis determined the potential need of unmanned and manned facilities in Low Earth Orbit (LEO) at each of three orbital inclinations: 28.5, 57 and 90 - 100 degrees. These functions include:

    1. Man-operated function

    2. OTV base function

    3. Man-tended free flyer function

b. Architectural options evaluation resulted in a Space System Architecture and evolution illustrated in Figure 1-3. This architecture includes a single Space Station at 28.5 degree orbital inclination that evolves to incorporate all major functions and the possibility of a second Space Station at polar Orbit by the end of the decade. System evolution is described as follows:

    1. During the first two years of the decade, the initial research, development, and production (RD&P) facility is placed in service with initial operating capability (IOC) in 1990. During this time period, launch of GEO and planetary spacecraft would continue to be performed by expendable upper stage vehicles, from the Space Shuttle. LEO spacecraft placement servicing and retrieval would be performed by a Teleoperator Maneuvering System (TMS) operated from the Shuttle.

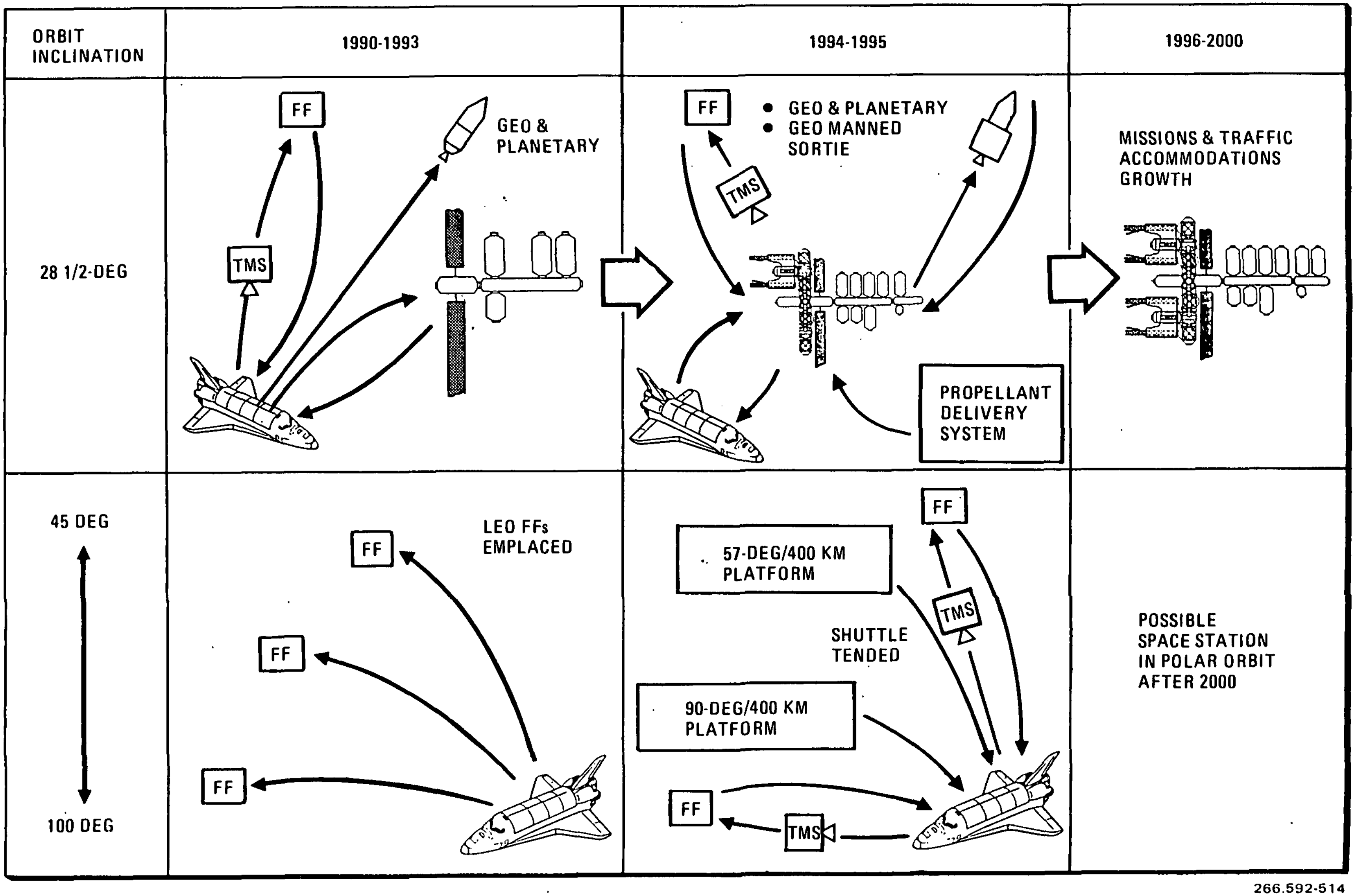

Figure 1-3. Missions Set Supported Space System Architecture

2. During the time period from 1992 to 1995, the initial RD&P facility would be augmented with an operations and servicing capability. Initially, in 1992, a TMS base will be incorporated on the station for servicing of LEO free flyers. Facilities for maintenance, repair and operation of a space based OTV will be integrated into the station during this time period. Considering the amount of propellant required to support OTV activities during this period, a Shuttle derived system (ET tanker) for delivery of large amounts of propellant to the station will also be required. Development of a system to maximize the amount of propellant which can be extracted from the shuttle external tank would also be developed. This approach will significantly enhance the economic benefits of the space based OTV and reduce the amount of propellant to be carried to the station by an ET tanker.

3. Full operational capability of the space based OTV on the Space Station would be available by 1994. Performance of all final technology development activities as required to support this operational capability will have been carried out on the station during the previous three years. The proposed approach is to develop this OTV launch capability as rapidly as possible since our study has shown that this activity provides the most significant quantifiable economic justification for a Space Station. In 1996, a second OTV maintenance, repair, and operational facility would be required to satisfy the free flyer traffic model.

4. During the initial two years of the decade, emplacement servicing and retrieval of free-flyers in LEO at the higher inclination orbits will be from the Shuttle utilizing TMS.

5. During the time period from 1992 to 1995, two multi-mission man-tended platforms will be installed, with the first one in a polar orbit and the second in a 57-degree orbit. These platforms provide a common bus for several mission payloads. Servicing of the platforms by Shuttle will be included. The capability to service several payloads on the platform in one Shuttle servicing operation is an additional benefit derived from the use of platforms.

6. Finally, as regards the polar orbit station, we foresee its implementation shortly after the year 2000 based on a projection of mission requirements as developed to date.

c. Functional analysis and subsystems architectural definition support the feasibility of implementing a multi-purpose Space Station in the decade of the nineties.

SECTION 2

SYSTEM REQUIREMENTS ANALYSIS

The missions requirements analysis of Volume II, Book 1, and the mission accommodations analysis contained in this Section resulted in a baseline missions set. From this set the time phased requirements for the Space Station system and system operational requirements were established as described in this Section.

2.1 MISSIONS REQUIREMENTS ANALYSIS

The potential Space Station missions that were initially identified were analyzed to determine the most acceptable mode of accommodation by the overall space system. Missions required frequent or continuous human presence to perform were allocated to manned space facilties. Missions requiring less frequent manned interaction or servicing were assigned as free flyers, i.e., unmanned payloads on autonomous spacecraft or platforms. The method of placement, servicing and retrieval of free flyers was also determined to establish traffic models for the Space Transportation System (STS) Shuttle, Teleoperator Maneuvering System (TMS), Shuttle/Expendable Upper Stages (EUS), and a space based reusable Orbital Transfer Vehicle (OTV). This subsection summarizes the results of these analyses.

2.1.1 MISSIONS REQUIREMENTS SUMMARY. The baseline missions set and missions requirements for the United States Space Program from the year 1990 through 2000 are summarized in Tables 2-1 through 2-4. This data, plus the more detailed missions descriptions data contained in Volume II, Book 1, Appendix I, was used to establish Space Station System requirements, STS requirements, and system and subsystems requirements for missions accommodations facilities.

2.1.2 MISSION ACCOMMODATIONS ANALYSIS. The detailed mission descriptions and requirements were analyzed to construct a time phased scenario of Space Station facilities which would accommodate as many of those missions as possible. The primary discrimination between these various facilities is the level of manned interaction required: man operated, requiring constant service or such frequent service as to prohibit having to rendezvous in order to gain access; man tended, requiring service at intervals at which it would be economical to place the mission on a free flyer and rendezvous for servicing; and nonserviced, requiring no manned interaction after emplacement in orbit.

The individual missions were grouped via three discriminators in order to recognize the pattern of development and growth required by the station:

a. Manned interaction was matched to the descriptions given above. This grouping was done qualitatively, as the missions were not in general described in detail sufficient to allow an economic analysis of the servicing/rendezvous question.

Table 2-1. Payload Requirements Summary Data - Man-Operated Accommodation Mode

GDC NO.	PAYLOAD ELEMENT NAME	DISCIPLINE	MISSION REQUIREMENTS: LAUNCH DATE YR(S)	MSN DUR (DAYS)	ORBIT: PREFERRED ALT (km)	PREFERRED INCL (deg)	ACCEPTABLE RANGE ALT (km)	ACCEPTABLE RANGE INCL (deg)	VIEWING DIRECTION	POINTING: ACCY (sec)	JITTER (sec/s)	OPER ACCEL LIMIT (g)	PHYSICAL: MASS (kg)	PRES'D VOL (m^3)	EXTNL SIZE L×W×H (m)	RESOURCES: POWER LEVEL, W (DUR, HR/DAY) OPER	PEAK	DATA K BPS (HR/DAY)	CREW: SIZE	TIME (AVG) HR/DAY	EVA REQ'D √	SVC REQ'D √	RECONFIG REQ'D √	COMMENTS
0005	Shuttle IR Tele. Facility	AST	90	1825	400	28.5	300-400	28.5-57	Inertial	96*		N/A	7018	0.36	11x4x4	1300 (18)	2735	1000	1	0.5	✓	✓		
0262	Measurement of Air Pollution from Satellites (MAPS)	ATR	90	365	400	57	200-600	28.5-90	Earth	7200		N/A	100	0.36	1x1x0.6	200		4600	1	0.2	✓	✓	✓	
0300	Human Research Lab	BLS	90	3600	ANY	ANY			N/A	N/A	N/A		7300	112.	N/A	2000 (8)	3080 (1)	128.	2	10		✓	✓	Volume = Total Module
0301	Animal & Plant Research Lab	BLS	90	3600	ANY	ANY			N/A	N/A	N/A	10^{-3} to 5×10^{-5}	4320	76.2	N/A	2000 (21)	4000 (3)	128	2	6		✓	✓	Volume = Total Module
0322	EVA Perf. & Productivity	OPM	90	3600	ANY	ANY			N/A	N/A	N/A		270	3.1	N/A	100 (0.3)			2	0.5	✓	✓	✓	TV Required
0400	Research & Development Facility	MPR	90	1460	>400	ANY	N/A	N/A	N/A	N/A	N/A	10^{-5}	1736	6.75	N/A	10K (22)	13K (2)	3 (24)	1	4				Vacuum Vent Required
1207	Electrophoresis Separation	MPC	90	7	ANY	ANY	N/A	N/A	N/A	N/A	N/A	10^{-4}	(300)	(2.7)	N/A	(500)			(1)	(0.5)				Ref. – 0400
1209	Metal Clusters & Crystal Growth	MPC	90	15	ANY	ANY	N/A	N/A	N/A	N/A	N/A	10^{-4}	(100)	(0.5)	N/A	(1000)			(1)	(1)				Ref. – 0400
1210	Enzyme Production & Separation	MPC	90	4	ANY	ANY	N/A	N/A	N/A	N/A	N/A	N/A			N/A				(1)	(2)				Ref. – 0400
1211	Silicon Crystals	MPC	90	30	ANY	ANY	N/A	N/A	N/A	N/A	N/A	10^{-4}	(300)	(1.2)	N/A	(5000) (8)			(1)	(8)				Ref. – 0400 For 30 Samples
1213	Chemical Reactions	MPC	90	7	ANY	ANY	N/A	N/A	N/A	N/A	N/A								(1)	(0.5)				Ref. – 0400
1214	Space Isothermal Furnace System (SIFS)	MPC	90	4	>250	ANY	N/A	N/A	N/A	N/A	N/A				N/A				(1)	(0.5)				Ref. – 0400
1300	Radiation Hardened Computer	INS	90	1825	ANY	ANY			N/A			N/A	50	0.36	.6x.5x.4	200 (24)		1000			✓			
1303	Plants in Controlled Env Life Support Sys (CELSS)	INS	90	180	ANY	ANY			N/A										1	0.2				Ref. –0341
2001	Strain & Acoustic Sensors	MTS	90	3650	LEO	ANY			N/A			N/A	50	0.36		100		1.0	1	0.1	✓	✓	✓	
2402	Advanced EVA Technology	CHF	90	3600	LEO	ANY			N/A	N/A	N/A	N/A	500	2.2		100			1	0.02	✓			

*At telescope interface with IPS.

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Table 2-1. Payload Requirements Summary Data - Man-Operated Accommodation Mode, Contd

GDC NO.	PAYLOAD ELEMENT NAME	DISCIPLINE	MISSION REQUIREMENTS: LAUNCH DATE YR(S)	MISSION REQUIREMENTS: MSN DUR (DAYS)	ORBIT: PREFERRED ALT (km)	ORBIT: PREFERRED INCL (deg)	ORBIT: ACCEPTABLE RANGE ALT (km)	ORBIT: ACCEPTABLE RANGE INCL (deg)	VIEWING DIRECTION	POINTING: ACCY (sec)	POINTING: JITTER (sec/s)	OPER ACCEL LIMIT (g)	PHYSICAL: MASS (kg)	PHYSICAL: PRES'D VOL (m^3)	PHYSICAL: EXTNL SIZE L X W X H (m)	RESOURCES: POWER LEVEL, W (DUR, HR/DAY) OPER	RESOURCES: POWER LEVEL, W (DUR, HR/DAY) PEAK	RESOURCES: DATA K BPS (HR/DAY)	CREW: SIZE	CREW: TIME (AVG) HR/DAY	CREW: EVA REQ'D √	SVC REQ'D √	RECONFIG REQ'D √	COMMENTS
2503	Space Component Lifetime Tech	SSS	90	3650	LEO	ANY			N/A			N/A	300	0	.2x.2x.2 (ea of 6)				1	0.2	✓		✓	Six Components
0174	Earth Obs Instru Devel (Microwave Tech)	ERS	91	730	1000	90	400-1600	28.5-90	Earth	360		N/A	200	0.36	1.5x1.x1.	200		1000	1	0.25			✓	
0340	$H_2O/O_2/CO_2/N_2$ Regenerative Systems	LFS	91	3650	ANY	ANY			N/A	N/A	N/A		1280	5.8	N/A	2400 (8)	4200 (16)	8	2	1			✓	
1108	Laser Communications	COM	91 92	5 5	ANY	ANY			Inertial	360		N/A	140	0.36	2x1x1	200 (3)	500 (20.5)	100K	1	0.5	✓			
1111	Millimeter Wave Propagation	COM	91 92 93	5 5 2920	ANY	ANY			Earth	3600		N/A	40	0.36	3x.5x3	25	100		1	0.25	✓		✓	
2002	Spacecraft Materials Tech	MTS	91	3300	LEO	ANY			N/A			N/A	150	0	5x1x0.1				1	0.1	✓	✓	✓	
2003	Materials and Coatings	MTS	91	3300	LEO	ANY			N/A			N/A	250	0	10x5x0.2				1	0.1	✓	✓	✓	
2101	Low-Cost Modular Solar Panels	ECN	91	3650	LEO	ANY			Solar	10000		0.1	30	0	5x6x 0.1				1	0.1	✓			
2401	Manipulator Controls Tech	CHF	91	365	LEO	ANY			N/A	N/A	N/A	N/A	600	12.		3150		1.0	2	0.4	✓			
2506	OTV Propellant Transfer and Storage	SSS	91	30	LEO	ANY			N/A			N/A	2000	0	8.5x4.6 x3.6	500 (2)			1	1.0				
2507	OTV Propellant Liquefaction	SSS	91	30	LEO	ANY			N/A			N/A	1000	0	3.5x2x2	350 (24)			1	1.0				
2508	OTV Docking & Berthing	SSS	91	30	LEO	ANY			N/A			N/A	5900	0	10x4.5 x4.5	500 (2)			1	2.0				TV Required
0000	Starlab	AST	92	1100	400	28.5	370-435	28.5-57	Inertial	150*		N/A	3280	0.36	13x7x4.5	2220 (18)	3890	16K	1	2	✓		✓	
0173	Shuttle Active Microwave Exper (SAMEX-C)	ERS	92	730	400	90	275-500	28.5-90	Earth	3600		N/A	2000	0.36	15x3x2	5K (12)	7500	5	1	0.2	✓		✓	
0176	EO Sensor/Technique/Anal/ Automated System Devel	ERS	92	1460	500	90	275-925	28.5-90	Earth	3600		N/A	2000	0.72	40x30x3	6K (12)		80K	2	1	✓	✓	✓	
0341	CELSS Experimental Systems	LFS	92	2190	ANY	ANY			N/A	N/A	N/A		2625	28	N/A	4400 (23)	6000 (1)		2	2		✓	✓	

*At telescope interface with IPS.

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Table 2-1. Payload Requirements Summary Data - Man-Operated Accommodation Mode, Contd

GDC NO.	PAYLOAD ELEMENT NAME	DISCIPLINE	MISSION REQUIREMENTS										PHYSICAL			RESOURCES								COMMENTS
			LAUNCH DATE YR(S)	MSN DUR (DAYS)	ORBIT				VIEWING DIRECTION	POINTING		OPER ACCEL LIMIT (g)	MASS (kg)	PRES'D VOL (m^3)	EXTNL SIZE L X W X H (m)	POWER LEVEL, W (DUR, HR/DAY)		DATA K BPS (HR/DAY)	CREW			SVC REQ'D √	RE-CONFIG REQ'D √	
					PREFERRED		ACCEPTABLE RANGE			ACCY (sec)	JIT-TER (sec/s)					OPER	PEAK		SIZE	TIME (AVG) HR/DAY	EVA REQ'D √			
					ALT (km)	INCL (deg)	ALT (km)	INCL (deg)																
1106	Large Deployable Antenna	COM	92 94	14 14	ANY ANY	ANY ANY			Earth	360		N/A	500	0.36	50x20x50	200	300	400	1	0.5	✓			
1200	Pilot – Biological Processing Facility	MPC	92	730	>400	N/A			N/A	N/A		10^{-3}	1050	4.3	N/A	8K (2)	10K (22)	3 (24)	1	4				Vacuum Vent Required
1208	Crystal Growth	MPC	92	6.5	ANY	ANY			N/A	N/A	N/A				N/A									Ref. – 0400
1305	Communication Satellite Service/Handling	INS	92	30	ANY	ANY			N/A			N/A												Ref. – 1106, 2504, 2505
2103	Ion Effects on LEO Power Systems	ECN	92	365	LEO	ANY			Solar	7200		N/A	150	0.36	5x6x0.1				1	0.1	✓		✓	
2504	OTV Payload Handling	SSS	92	30	LEO	ANY			N/A			N/A	2000	0	4x4.5 x4.5	300 (2)			2	8				TV Required
2505	Payload Servicing & Repair	SSS	92	90	LEO	ANY			N/A			N/A	500	0	9x4.5 x4.5				1	1	✓			TV Required
2509	OTV Maintenance	SSS	92	30	LEO	ANY			N/A			N/A	3000	0	8.5x7.5 x7.5	500 (4)		4.0	4	13	✓			TV Required
2601	Light Weight Cryo Heat Pipes	FTP	92	250	LEO	ANY			N/A			N/A	1000	0.36	15x1.0 x1.0	200	**	2	1	1.6	✓	✓		**5000W Reqd 12 Times/ Mission for 5 Min Each
1109	Open Envelope Tube	COM	93 94	7 7	ANY	ANY			Inertial				157	0.36	0.2x0.2 x6	500	2000	100	1	0.25	✓			
0034	High Resolution X and Gamma Ray Spectrometer	HEN	93	1080	400	28.5			Inertial	360*		N/A	1768	0.36	2.1x2.1 x2.1	530 (18)	830 (6)	30	1	0.5	✓	✓		
0202	Meteorology Instru Group Devel Payload	WCL	93	365	400	57	300-500	28.5-90	Earth	360		N/A	1170	0.72	1.6x4.4 x4.4	1140 (24)		3000	2	0.4	✓	✓	✓	
2004	Thermal Shape Control	MTS	93	550	LEO	ANY			N/A			N/A	1000	0.36	20x10x.2	3000	6000	1.0	1	0.1	✓			
0032	Large Area Modular Array	HEN	94	1640	400	28.5			Inerial	180		N/A	9516	0.36	7.8x4.4 x4.4	3400 (20)		125	1	0.5	✓	✓		
0175	Earth Obs Instru Devel (Extra Visible & RF)	ERS	94	730	400	90	275-1000	28.5-90	Earth	1800		N/A	1000	0.36	8x4x2	500	700	1000	1	0.25	✓	✓	✓	
0265	Upper Atmosphere Research Payload-Development	ATR	94	550	400	57	400-600	28.5-90	Earth-Solar	36		N/A	2500	0.72	4.5x4.5x2	4K (4)		500	2	0.8	✓	✓	✓	

*At telescope interface with IPS.

260.592-49.3

Table 2-1. Payload Requirements Summary Data - Man-Operated Accommodation Mode, Contd

GDC NO.	PAYLOAD ELEMENT NAME	DISCIPLINE	MISSION REQUIREMENTS										PHYSICAL			RESOURCES								COMMENTS
			LAUNCH DATE YR(S)	MSN DUR (DAYS)	ORBIT				VIEWING DIRECTION	POINTING		OPER ACCEL LIMIT (g)	MASS (kg)	PRES'D VOL (m^3)	EXTNL SIZE L X W X H (m)	POWER		DATA K BPS (HR/DAY)	CREW			SVC REQ'D √	RE-CONFIG REQ'D √	
					PREFERRED		ACCEPTABLE RANGE			ACCY (sec)	JITTER (sec/s)					LEVEL, W (DUR, HR/DAY)			SIZE	TIME (AVG) HR/DAY	EVA REQ'D √			
					ALT (km)	INCL (deg)	ALT (km)	INCL (deg)								OPER	PEAK							
0401	R&D/Proof of Concept Facility	MPR	94	2600	>400	ANY			N/A	N/A	N/A	10^{-5}	3224	11.95	N/A	25K (22)	35K (2)	6 (24)	1	8				Vacuum Vent Required
1107	RFI Measurements	COM	94	21	ANY	ANY			Earth	3600		N/A	50	0.36	15x15x15	100	300	1K	1	0.5	✓		✓	
1201	Pilot – Containerless Processing Facility	MPC	94	1095	>400	ANY			N/A	N/A	N/A	10^{-3}	3900	12.9	N/A	12K (4)	25K (4)	3 (8)	1	8				Vacuum Vent Required
1202	Pilot-Furnace Processing Facility	MPC	94	1095	>400	ANY			N/A	N/A	N/A	10^{-5}	4452	12.05	N/A	30K (12)	50K (12)	10 (24)	1	4				Vacuum Vent Required
2005	Dynamics of Flimsy Struct	MTS	94	1460	LEO	ANY			N/A			N/A	1000	0.72	100x20 x2.5	1000 (24)		1.0	1	0.1	✓			
2006	Active Optics Technology	MTS	94	1000	LEO	ANY			Inertial			N/A	10000	0.36	16x12x16	1000			1	0.2	✓	✓		
2201	Attitude Control – System Identification Exper	CSE	94	365	LEO	ANY			N/A			N/A	100	0.36	100x20 x2.5**	1000		1.0	2	0.2	✓		✓	**Uses Structure From 2005
2202	Attitude Control – Adaptive Control Experiment	CSE	94	365	LEO	ANY			N/A			N/A	100	0.36	100x20 x2.5**	1000		1.0	2	0.2	✓		✓	**Uses Structure From – 2005
2301	Controlled Acceleration Propulsion Tech	PPN	94	180	LEO	ANY			N/A			N/A	45	0.36	0.6x0.4 x0.4	1500			1	0.2	✓	✓		Propellant Required
2502	Advanced Control Device	SSS	94	730	LEO	ANY			N/A			N/A	400	0.36	100x20 x2.5**	1000		1.0	2	0.2	✓		✓	**Uses Structure From – 2005
1110	Spaceborne Interferometer	COM	95 97	15 15	ANY	ANY			Earth	360		N/A	60	0.36	30x.2x.2	100 (2)	150 (0.5)	500	1	0.5	✓			
1203	Commercial-Biological Processing Facility	MPC	95	1825	>400	ANY			N/A	N/A	N/A	10^{-3}	2100	8.6	N/A	16K (4)	20K (20)	6 (24)	1	8				Vacuum Vent Required
1301	Full-Body Teleoperator	INS	95	1460	ANY	ANY			N/A			N/A	300	1.5		500- 1000								
2104	Large Solar Concentrator	ECN	95	365	LEO	ANY			Solar	900		N/A	5000	0.36	10x10x10				1	0.2	✓			
2203	Attitude Control – Distributed Control Exper	CSE	95	365	LEO	ANY			N/A			N/A	100	0.36	100x20 x2.5**	1000		1.0	2	0.2	✓		✓	**Uses Structure From -- 2005
2510	Tether Dynamics Tech	SSS	95	3	LEO	ANY			N/A			N/A	3000	0.36	4x4x2				1	3				

*At telescope interface with IPS.

266.692 40.4

Table 2-1. Payload Requirements Summary Data – Man-Operated Accommodation Mode, Contd

GDC NO.	PAYLOAD ELEMENT NAME	DISCIPLINE	MISSION REQUIREMENTS: LAUNCH DATE YR(S)	MSN DUR (DAYS)	ORBIT: PREFERRED ALT (km)	PREFERRED INCL (deg)	ACCEPTABLE RANGE ALT (km)	ACCEPTABLE RANGE INCL (deg)	VIEWING DIRECTION	POINTING: ACCY (sec)	JITTER (sec/s)	OPER ACCEL LIMIT (g)	PHYSICAL: MASS (kg)	PRES'D VOL (m^3)	EXTNL SIZE L X W X H (m)	RESOURCES: POWER LEVEL, W (DUR, HR/DAY) OPER	POWER PEAK	DATA K BPS (HR/DAY)	CREW SIZE	CREW TIME (AVG) HR/DAY	EVA REQ'D √	SVC REQ'D √	RECONFIG REQ'D √	COMMENTS
0036	Spectra of Cosmic Ray Nuclei	HEN	96	365	400	57	370-435	28.5-57	Anti-Earth	3600		N/A	3082	0.36	3.3x4.8 x3.8	731 (22)	785 (2)	102	1	0.2	✓	✓		
0037	Transition Radiation and Ionization Colorimeter	HEN	96	700	400	57	370-435	28.5-57	Anti-Earth	3600		N/A	5750	0.36		550 (24)		10	1	0.5	✓	✓		
0242	Incoherent Scatter Radar	STR	96 98	365 {	400 400	0 90	400-500 400-500	0-28.5 80-100 }	Earth, Celestial	18000		N/A	1000	0.36	25x25x15	1500			1	0.5	✓			
0342	Dedicated CELSS Module	LFS	96	1460	ANY	ANY			N/A	N/A	N/A		10500	111	N/A	18000 (23)	22000 (1)		2	6		✓	✓	Volume = Total Module
0343	CELSS Pallets	LFS	96	2190	ANY	ANY			N/A	N/A	N/A		1300		1x2.5 x0.5	600 (24)			2	0.5		✓		
0179	Imaging Radar for Earth Resources Inventory & Monitoring	ERS	96	1095	400	57	300-500	28.5-90	Earth	360		N/A	2000	0.36	15x3x2	5K	7.5K	20	1	0.2				
1304	Controlled Environment Life Support Systems (CELSS)	INS	96	180	ANY	ANY			N/A			N/A	[1500]	[9.3]		[300]	[1000-2500]		1	0.2				Ref. 0342
2105	Solar Pumped Lasers	ECN	96	270	LEO	ANY			Solar	900		N/A	200	0	10x10 x10**				1	0.2	✓		✓	**Uses – 2104 Collector
2106	Laser/Electric Energy Conversion	ECN	96	450	LEO	ANY			Solar	900		N/A	500	0	10x10 x10**				1	0.2	✓		✓	**Uses – 2104 Collector
2204	Advance Adaptive Control Technology Demo	CSE	96	365	LEO	ANY			N/A			N/A	100	0.36	100x20 x2.5**	1000		1.0	2	0.2	✓		✓	**Uses Structure From – 2005
2302	Laser Propulsion Test	PPN	96	180	LEO	ANY			Solar			N/A	100	0.36	1.5x.5 x.5	200		5	1	0.25	✓	✓		Collector & Laser From 2104 & 2105. GH_2 Required
2501	Liquid Droplet Radiator	SSS	96	365	LEO	ANY			N/A			N/A	1000	0.36		1000		1.0	1	0.1	✓			
0243	Topside Digital Ionosonde HF Radar	STR	97 99	365 {	400 400	0 90	400-500 400-500	0-28.5 80-100 }	Earth			N/A	500	0.36	200 x200x3	1500			1	0.5	✓			
1204	Commercial-Containerless Processing Facility	MPC	97	1095	>400	ANY			N/A	N/A	N/A	10^{-3}	5700	20.3	N/A	26K (20)	38K (4)	6 (24)	1	8				Vacuum Vent Required

*At telescope interface with IPS.

266.592 49.6

Table 2-1. Payload Requirements Summary Data - Man-Operated Accommodation Mode, Contd

GDC NO.	PAYLOAD ELEMENT NAME	DISCIPLINE	MISSION REQUIREMENTS: LAUNCH DATE YR(S)	MSN DUR (DAYS)	ORBIT: PREFERRED ALT (km)	PREFERRED INCL (deg)	ACCEPTABLE RANGE ALT (km)	ACCEPTABLE RANGE INCL (deg)	VIEWING DIRECTION	POINTING: ACCY (sec)	JITTER (sec/s)	OPER ACCEL LIMIT (g)	PHYSICAL: MASS (kg)	PRES'D VOL (m^3)	EXTNL SIZE L X W X H (m)	RESOURCES: POWER LEVEL, W (DUR, HR/DAY) OPER	PEAK	DATA K BPS (HR/DAY)	CREW: SIZE	TIME (AVG) HR/DAY	EVA REQ'D √	SVC REQ'D √	RECONFIG REQ'D √	COMMENTS
1205	Commercial-Furnace Processing Facility	MPC	97	1500	>400	ANY			N/A	N/A	N/A	10^{-5}	6325	22.5	N/A	40K (20)	70K (4)	10 (24)	1	8				Vacuum Vent Required
1212	Heat Resistant Alloys	MPC	97	30	ANY	ANY			N/A	N/A	N/A		(5000)			(100K) ((6))			(1)	(8)				Ref. – 1205 for 30 Samples
2107	Solar Sustained Plasmas	ECN	97	450	LEO	ANY			Solar	900		N/A	2000	0	10x10 x10**				1	0.2	✓		✓	**Uses – 2104 Collector
2108	Space Nuclear Reactor	ECN	97	2560	LEO	ANY			N/A			N/A	2500	0.36	100x4x4				1	0.1	✓			NASA Cost Share is 1/3
0151	Detection & Monitoring of Episodic Events	CRM	98	1825	450	90	400-500	80-100	Earth	6		N/A	3500	0.36	16x10x3	3000		300K	2	1	✓	✓	✓	
0161	Earth Science Research-Geophysical Investigation	GPF	98	800	400	90	275-500	85-95	Earth	1800		N/A	400	0.36	100x2x2	130 (24)	1200	30	1	0.5				
0245	Space Plasma Physics Payload-Advanced	STR	98	730	400	57	250-500	57-90	Earth, Solar	3600		N/A	3183	0.36	5x300 x10	3225 (1)	12K (0.1)	12K	1	0.5		✓		
0263	CO_2 LIDAR for Atmospheric Measurements	ATR	98	1825	400	57	300-500	285-90	Earth	3600		N/A	4000	0.36	9x4.5 x4.5	25K		250	1	0.25	✓	✓	✓	
0031	High Throughput Mission	HEN	99	1460	400	28.5			Inertial	180		N/A	10000	0.36		2000 (20)		125	1	1	✓	✓		
0201	Satellite Doppler Meteorological Radar Tech Devel	WCL	99	365	400	57	300-500	28.5-90	Earth	3600		N/A	2600	0.36	50x5.2 x5.2	6K		120K	2	0.4	✓	✓	✓	
0244	Solar Terrestrial Observatory – Advanced	STR	00	2190	400	57	300-500	57-90	Solar, Earth	1800		N/A	16500	1.44	13x300 x10	10K (12)	21K (12)	42K	2	1.33	✓	✓	✓	

*At telescope interface with IPS.

260.592 49.6

Table 2-2. Baseline Missions Set - LEO/HEO Free Flyer Payload Model

GDCD NO.	PAYLOAD ELEMENT NAME	ORBIT ALTITUDE (KM)	INCLINATION (DEG)	UNIT WT (KG)	LENGTH (M)	P/L ELEMENT DEFINITION: INTEG. INST. PKG. ①	P/L ELEMENT DEFINITION: SPACECRAFT	SPACECRAFT INCL. ORBIT XFER PROPUL.	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	RESCHEDULED? YES (NO. YRS)	RESCHEDULED? NO
	ASTROPHYSICS																				
	• Astronomy																				
0001	Large Deployable Reflector	700	28.5	55,000			✓										E		S/C	✓(3)	
0003	Very Long Base-Line Interferometer Demo	400	57	1,354	5	✓								E	S	S	R				✓
0004	Space Telescope	600	28.5	11,600	13.1		✓				E		S/C		S/C	R					✓
	• High Energy (Cosmic, γ, X-Ray)																				
0030	Gamma Ray Observatory (1988 Launch)	400	28.5	11,000			✓	✓	S	S	S	R									✓
0033	Adv X-Ray Astrophysics Facility	500	28.5	10,267	12.8		✓			E		S/C		S/C		S/C		S/C			✓
0038	X-Ray Timing Explorer	400	28.5	1,000	2		✓	✓	E		R										✓
	• Solar Physics																				
0060	Solar Internal Dynamic Mission	400	99	4,540			✓	✓		E	R										✓
0061	Solar Corona Diagnostic Mission	400	28.5	1,800			✓					E	R							✓(1)	
0062	Advanced Solar Observatory	400	57	12,500	8.2	✓								E		S		S		✓(2)	
	EARTH EXPLORATION																				
	• Earth Resources																				
0172	Operational Land Systems	500	90	2,000	4		✓	✓	E		S/C		S/C		S/C		S/C		R		✓
0180	Freeflying Imaging Radar Exp (FIREX)	400	90	2,000	4	✓					E			S				R		✓(1)	
0181	Z-Continuous Coverage	1000	100	8,578	16		✓	✓							E	S/C	R			✓(2)	
0182	Z-Hydrologic Cycle Priority	1000	100	8,708	16		✓	✓									E	S/C	R	✓(2)	
0183	Z-Special Coverage	1000	100	18,821	17		✓	✓											E	✓(2)	
	ENVIRONMENTAL OBSERVATIONS																				
	• Weather/Climate, Ocean, Solar/Terrestrial, Atmos Research																				
0205	Meteorology Inst Grp Ops P/L	400	57	2,000	4.4	✓								E		S		R		✓(1)	
0207	Tiros Follow-on ③	800	98	2,000	9		✓				E										✓
0221	Ocean Instrument Payload	500	98	1,600	10	✓							E		S			E R		✓(1)	
0222	Ocean Topography Exp. (TOPEX)	1384	63.4	1,600	6		✓		S			S			S		R				✓
0241	Earth Radiation Budget Exp. (ERBE) (1988 Lch)	600 800	46 98	55 55	1 1	✓ (Piggy Back P/L)				E	R										✓
0266	WINDSAT	800	98	2,260	4.5		✓							E		S		S		✓(3)	
0267	Upper Atmosphere Research P/L	400	57	2,500	4.5	✓							E		S		R				✓

266.592-19.1

Table 2-2. Baseline Missions Set - LEO/HEO Free Flyer Payload Model, Contd

GDCD NO.	PAYLOAD ELEMENT NAME	ORBIT ALTITUDE (KM)	INCLINATION (DEG)	UNIT WT (KG)	LENGTH (M)	P/L ELEMENT DEFINITION: INTEG. INST. PKG. ①	P/L ELEMENT DEFINITION: SPACECRAFT	SPACECRAFT INCL. ORBIT XFER PROPUL.	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	RESCHEDULED? YES (NO. YRS)	RESCHEDULED? NO
	COMMERCIAL																				
	• Mat Processing																				
1206	Electrophoresis F/F – Biologicals (Initial Lch 1986)	>400	Any	9,987	5.5		✓	✓	E 9S	8S R	6S R	4S R	2S R	R							✓
1000	Geological Reconnaissance	500	90						E [Accommodated by GDCD 0172; 0174; 0175 for development)												✓
1002	Worldwide Cotton Acreage & Prod	500	45						E [Accommodated by GDCD 0172]												✓
1003	Petroleum and Mineral Location	920	99.2						E [Accommodated by GDCD 0172]												✓
1302	Gamma Ray Astronomy	400	28.5						E [Accommodated by GDCD 0030]												✓
	P/L REASSIGNED FROM ATTACHED MODE																				
	ASTROPHYSICS																				
0035	High Energy Isotope Experiment	400	57	3,000		✓②										E	S	S	R	✓ (2)	
	EARTH EXPLORATION																				
0152	Geoscience – Crustal Dynamics Studies	500	50	185		✓			E		S	R									✓
1071	Renewable Resources – Earth Sci	400	90	2,000		✓②									E	S/C	S/C	S/C	S/C	✓ (1)	
0177	Geoscience – Geology Rem. Sensing	500	90	2,000		✓			E	C	C	C	C	R							✓
	ENVIRONMENTAL OBSERVATIONS																				
0246	Solar Terrestrial Observatory	400	57	16,000		✓②							E	R						✓ (1)	
0247	Space Plasma Physics P/L	400	57	3,183		✓②					E	R								✓ (1)	
0261	High Res. Doppler Imager	400	57	10,800		✓			E	R											✓
0264	LIDAR Facility	400	57	1,900		✓					E S/C	R								✓ (1)	

NOTES: TMS available in 1990; OTV available in 1994.
E = Emplace, S = Service, C = Configuration Change, R = Retrieve

① These P/L elements assume accommodation on a platform or leasecraft-type spacecraft which has orbit transfer propulsion.

② Originally defined as attach payload element with servicing at 180 day intervals. Redefinition as free flyer would require redesign for 360 day service interval.

③ Two satellites required.

266.692-19.2

Table 2-3. Baseline Missions Set - Geo Payload Model

GDCD NO.	PAYLOAD ELEMENT NAME	ORBIT ALTITUDE (KM)	INCLINATION (DEG)	UNIT WT (KG)	LENGTH (M)	P/L ELEMENT DEFINITION: INTEG. INST. PKG. (1)	P/L ELEMENT DEFINITION: SPACECRAFT	SPACECRAFT INCL. ORBIT XFER PROPUL.	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	RESCHEDULED? YES (NO. YRS)	RESCHEDULED? NO
	ASTROPHYSICS																				
	• Astronomy																				
0002	Far UV Spectroscopy Explorer (Lch in 1989)	Geo	28.5	1,360	(Incl	AKM)															
	ENVIRONMENTAL OBSERVATIONS																				
	• Weather/Climate																				
0203	Lightning Mapper	Geo	0	900(1)	6												E			✓(2)	
0204	Geosync Microwave Sounder	Geo	0	5,850	10														E	✓(3)	
0206	Goes Follow-On (1) 5-each at 900 Kg/flight (2) 3-each at 500 Kg/flight	Geo	0	500(2)	3.6								E						R		✓
	COMMERCIAL MISSIONS																				
	• Communications																				
1001	Remote Atmospheric Sensing	Geo	0	[300-1000]					E	[Accommodated by GDCD 0206 and for development GDCD 0262]											✓
1100	*Small Communications Satellites*	Geo	0	<816	2				6	6	8	10	10	10	5	7	6	6	7		✓
1101	Medium Communications Satellite	Geo	0	<2,041	4				4	4	6	4	3	4	3	3	3	3	3		✓
1102	Large Communication Satellite	Geo	0	>2,313	5				5	6	6	7	10	10	12	13	14	14	17		✓
	• Platforms																				
1103	Experimental Geo Platform	Geo	0	5,450	<10				E		S										✓
1104	Operational Geo Platform (4)	Geo	0	5,450	<10								2E	E S	2ES	E2S	2ES	E S	2E 2S		✓
	OPERATIONAL																				
	• Other Missions																				
4000	Manned Geo Sortie Capsule	Geo	0	4,535	4.4													E	E	✓(4)	
4001	Manned Geo Support Module	Geo	0	8,160	6.8															✓(2)	
	<u>DOD SCENARIO</u> – Derived from Nominal Mission Model, Rev. 6, MSFC PS01, 9/30/82 and DoD MSN Model Rev. 12, Summary Level (Equivalent Qty Flights Both Geo & Heo Missions)		ETR						4	4	4	5	6	7	5	5	8	9	9		✓
			WTR						5	4	3	4	4	2	3	4	3	4	4		✓

NOTES: TMS available in 1990; OTV available in 1994.
E = Emplace, S = Service, C = Configuration Change, R = Retrieve

(1) *These P/L elements assume* accommodation on a platform or leasecraft-type spacecraft which has orbit transfer propulsion.

(2) Originally defined as attach payload element with servicing at 180 day intervals. Redefinition as free flyer would require redesign for 360 day service interval.

(3) Two satellites required.

(4) 11 Emplacement flights of 5450 Kg each (6 for one platform and 5 for second platform) plus 8 Revisit Flights.

266.592-19.3

Table 2-4. Baseline Missions Set - Planetary Payload Model

GDCD NO.	PAYLOAD ELEMENT NAME	ORBIT ALTITUDE (KM)	INCLINATION (DEG)	UNIT WT (KG)	ESCAPE ΔV FROM LEO (M/S)	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	PLANETARY EXPLORATION	SPACECRAFT TO ESCAPE FROM 370-400 CIRCULAR ORBIT														
	• PLANETARY OBSERVATIONS															
0103	MARS GEOCHEM/CLIMATOLOGY ORBITER		28.5	5,600	3,380			E								
0104	MARS ARONOMY ORBITER			5,600	3,380			E								
0105	VENUS ATMOSPHERIC PROBE								E							
0106	LUNAR GEOCHEMISTRY PROBE			480					E							
0107	TITAN PROBE			960	7,390						E					
0108	SATURN ORBITER (TITAN FLY-BY)			1,800									E			
0109	MARS SURFACE NETWORK (LANDER)												E			
0110	SATURN PROBE												E			
	• SOLAR SYSTEM MISSIONS															
0121	COMET RENDEZVOUS			2,200				E								
0122	MAIN BELT ASTEROID RENDEZVOUS			2,700				E								
0123	COMET SAMPLE RETURN (HMP)			1,200						E						
0124	NEAR EARTH ASTEROID RENDEZVOUS		28.5	1,170	4,120								E			

NOTES: TMS AVAILABLE IN 1990; OTV AVAILABLE IN 1994
E = EMPLACE, S = SERVICE, C = CONFIGURATION CHANGE, R = RETRIEVE

266.592-12.2

b. Orbit altitude and inclination were used to identify the locations of facilities required by the mission set.

c. The requested schedule for each mission was used to define the growth of each facility type in each orbit location.

Two complete cycles of iteration between the Mission Implementation and Mission Analysis Groups were used to solidify the capabilities required by the Mission Set. The general pattern followed was for the Missions Analysis Group to provide the Implementation Group with the Mission Requirements Summary (see Subsection 2.1.1) which specified parametive values such as scheduling, power, size, man hours required, etc. The individual missions were segreated into time-phased sets for each of the categories described above. This segregated set was returned to Mission Analysis for review, resulting in a revision of the constraints on scheduling and location of the missions. At this time, new missions, and new and revised data on old missions were incorporated.

Of the 149 missions identified (Figure 2-1), the first iteration assigned ninety-nine as station candidates. Eighty-one of these had requirements which dictated assignment to the station, and the remaining eighteen were also acceptable as free flyers. The fifty missions which were not compatible with the station were assigned as free flyers. Of this group, two were GEO platforms, twenty-three had requirements which dictated their assignments as independent satellites.

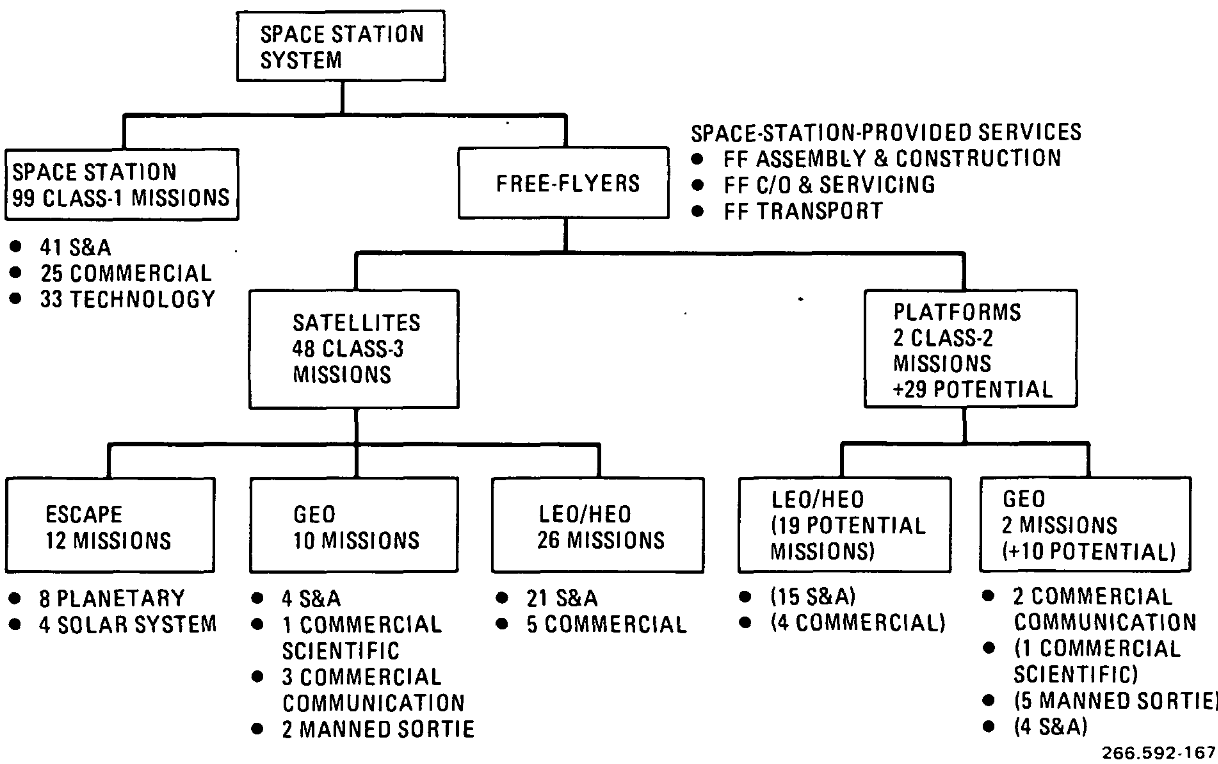

Figure 2-1. Total Mission Set Accommodation System

The second iteration resulted in the scenario which was designated as the baseline for accommodation. Of the total group of 149 missions, ninety-one were assigned to the station (eight-one required, ten compatible). Fifty-eight were assigned as free flyers (eleven on platforms, forty-seven as free flyers).

The major factors, which caused the re-assignment of missions from one facility to another were funding and scheduling. The establishment of the baseline mission set is discussed in greater detail in Volume II, Book 1, Subsection 4.4.

2.1.3 TRANSPORTATION MISSIONS ANALYSIS. Requirements for spacecraft placements, servicings and retrievals (Tables 2-2, 2-3 and 2-4) form the basis for this analysis. Spacecraft which have their own propulsion system are first factored out of the list of potential operations. Individual operations are separated by inclination and energy requirement. The majority of operations are at a near 28-1/2-degree inclination and fall into two general energy levels, TMS class and OTV class. TMS capabilities are taken from NASA studies and OTV capabilities are derived from the vehicle concept described in Subsection 2.2.1.

Individual operations are manifested to form TMS or OTV missions. In general, the TMS is assumed to take only a single satellite or to perform only a single servicing operation per mission while the OTV can be equipped with a bus structure holding up to four small satellites for placement.

Once manifested, the effects of vehicle IOC and availability are assessed. The system trades which led to the determination of these parameters are presented in Subsection 3.1.2.

The TMS and OTV Baseline Mission Models determined through this analysis are used to develop propellant requirements per year. The propellant requirements and their effect on the Earth-to-LEO propellant transport systems are examined in Subsection 3.3.3.

2.1.3.1 OTV Mission Analysis. Three quarters of all OTV missions originate at a 28.5-degree inclination LEO orbit. The remaining 25 percent originate from 57-degree and higher inclination LEO orbits. Most of the latter are DOD missions which are launched into near polar inclinations, only a small fraction enter the intermediate inclinations. This discussion will concentrate on the 28.5-degree operations which are suitable for space-based OTV operation early in the decade. Higher inclination payload placements are too infrequent and too scattered in inclination to support an OTV facility until late in the 1990s. A summary of OTV missions is presented in Table 2-5.

Table 2-6 summarizes the 28.5 degree mission model. Most missions are communications satellite emplacements. Numbers in parenthesis are those missions of the total which must be performed by the uprated capability OTV with four sets of propellant tanks. All other missions after 1993 with the exception of a few remaining Centaur or IUS expendable missions are performed with the baseline two-tank aerobraked OTV with 11 klb to GEO (and return empty) capability.

Table 2-5. OTV Mission Summary 1990-2000

	Percent of Missions	Percent of Total
28-1/2° Operations - Total	226	77
GEO Placements	196	6
Escape Missions	12	4
Manned GEO	6	2
Miscellaneous*	13	4
57°-90° Operations - Total	67	23
Payload Placements	44	15
Miscellaneous*	23	8
Total Operations	293 Missions - 27 Per Year Average	

*Includes Servicing, Retrievals and Unplanned Operations

For missions other than single satellite emplacements additional weight was assumed for other missions requirements. These include 500 lb for a 4 satellite bus structure, 300 lb for closeup imaging system and short remote manipulator for retrieval and 1800 lb + 1/10 the satellite weight for the servicing module with all associated equipment and the propellants required for refilling satellite ACS tankage. Some low payload mass missions are combined together.

An OTV deployment cycle is required to determine which missions will be performed by the OTV and which will be performed by existing expendable stages. Several development cycles were assessed for the Space-Based OTV and the associated servicing facilities. The following development plan was selected based on total programmatic costs and expected technology developments derived from the Orbit Transfer Vehicle Servicing Contract NAS8-35039.

Up to six Technology Development Missions (TDM) of one to eight week duration occur in 1991 and 1992. The first missions address Propellant Transfer/Storage/Conservation and involve tests with small cryogenic tanks carried and mounted to the Station. The later tests examine OTV Docking and Berthing and Maintenance. A TMS is used for the active tests and a simulated (static) OTV for the maintenance tasks. Additional TDMs may explore more details of large scale propellant transfer, as from an ET Tanker into large Space Station dewars.

Table 2-6. OTV Missions - 28.5-Degree Inclination Operations

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
EMPLACE – PLANNED	6 (1)	7	8	9	12 (2)[2]	12 (1)[2]	12 (2)[2]	13 (1)[2]	16 (2)[2]	13 (2)[2]	17 (3)[2]
– UNPLANNED	–	–	–	–	–	1/2[1]	1 1/2[1]	–	1/2[1]	1[1]	–
SERVICE – PLANNED	–	–	1	–	–	1	1	2	1	1	3
(IN SITU) – UNPLANNED	–	–	–	–	–	–	–	–	–	–	–
RETRIEVE – PLANNED	–	–	–	–	–	–	–	–	–	–	–
– UNPLANNED	–	–	–	–	–	1/2[1]	1 1/2[1]	–	1/2[1]	1[1]	–
ESCAPE – (THRU 1996, ALL ARE CENTAUR MISSIONS)	–	–	4	2	1	1	–	4[2]	–	–	–
DOD (ALL EMPLACE) (75% MANIFESTING EFF.)	4	4	4	5	6	7	5	5	8	9	9
MANNED SORTIE	–	–	–	–	–	1[2]	1[2]	1[2]	1[2]	1[2]	1[2]
SMOOTHING ADJUSTMENT	–	+2	-2	–	–	–	–	–	–	–	–
TOTAL MISSIONS – 226	10	13	15	16	19	23	22	25	27	26	30
TOTAL OTV MISSIONS[3] – 162	–	–	–	–	14	18	22	25	27	26	30
	–	–	–	–	–	(2)[2]	(3)[2]	(6)[2]	(3)[2]	(3)[2]	(4)[2]

NOTES

(1) *COMBINED EMPLACE/RETRIEVAL MISSION*

(2) 4 TANK AEROBRAKED OTV -- ALL OTHERS 2 TANK AEROBRAKED OTV (11 KLB TO GEO) OR CENTAUR/IUS EXPENDIBLES.
OF 162 OTV MISSIONS:
132 ARE 2 TANK GEO DELIVERY/RETRIEVAL
9 ARE 2 TANK GEO SERVICE
11 ARE 4 TANK GEO DELIVERY/RETRIEVAL
6 ARE 4 TANK GEO MANNED SORTIE
4 ARE 4 TANK PLANETARY ESCAPE (OTV RECOVERED)

DELIVER = W SATELLITE
RETRIEVAL = W SATELLITE + 300 LB
SERVICE = 1/10 W SATELLITE + 1800 LB

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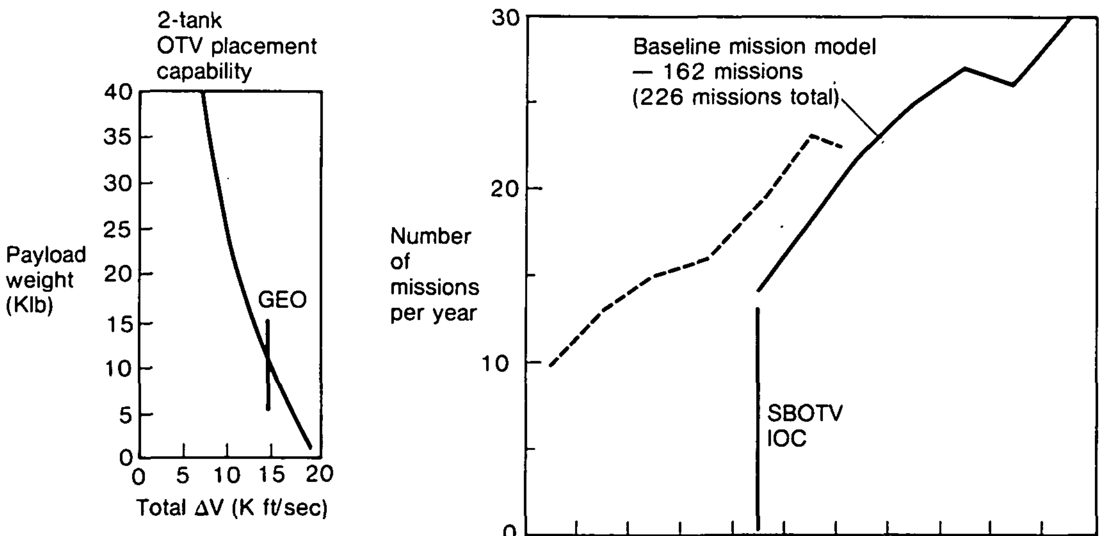
In 1992-1993, 3-4 more TDMs occur with Shuttle-Centaur acting as a simulated OTV. Propellant topping off, docking, command & control, payload integration, etc., are tested and evaluated. Centaur testing potentially includes mission to deliver a payload to GEO, return to LEO and dock to Station (Centaur may need assistance of TMS). Centaur is then checked out and retanked at the Station, integrated with a new payload (perhaps a dummy) which is then delivered to another orbit.

In mid-1993 the servicing facility buildup commences. Depending on the exact configuration, between 4 and 8 STS flights would be required to take up the Hangar, maintenance module, command module, required truss supports, access passageways, propellant tanks and miscellaneous servicing equipment. After facilities assembly and checkout the OTV itself is taken up and assembled late in the year.

After checkout and an extensive test program, the first operational flight of the two tank OTV occurs in 1994. An aerobrake may be part of the initial vehicle or added the next year. Up to 14 operational missions occur in 1994. A second OTV is delivered the next year with 4 tanks to support manned missions and other larger payloads. Up to 18 operational missions could be accommodated in 1995. After 1996, all the missions required by the mission module can be accommodated. A second OTV hangar facility is added in 1997 to allow simultaneous OTV checkout and payload integration and reduce scheduling concerns.

Figure 2-2 summarizes the total OTV model. It exhibits a fairly constant growth rate of about 9 percent. Large payloads (greater than 11,000 lb to GEO) are launched with increasing frequency as the decade draws to a close.



Mission type	90	91	92	93	94	95	96	97	98	99	2000
Placement	(10)	(13)	(10)	(14)	13(5)	15(5)	19	19	25	23	26
Retrieval	–	–	–	–	–	1	2	–	1	1	–
Service in-situ	–	–	(1)	–	–	1	1	2	1	1	3
Escape	–	–	(4)	(2)	(1)	(1)	–	4	–	–	–
Manned sortie	–	–	–	–	–	–	–	–	–	1	1

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Figure 2-2. Space-Station-Based OTV Missions Per Year

One conclusion about OTV capability becomes apparent in examination of the average energy requirement for each mission. The average payload weight manifesting efficiency for the OTV is only 77 percent. The primary limitation is the expected satellite weights predicted by SPACECOM and others. Even when up to four satellites are packaged together for flight, the average payload weight delivered is only 8,500 lb. The 11,000 lb deliver to GEO capability appears to be in excess of real requirements. A smaller OTV with a payload capability of 9,000-9,500 lb (two tank aerobraked) will result in a more efficient, less costly vehicle which still has the capability to carry over 20 klb to GEO when augmented with four tanks. Even more can be carried if the vehicle is staged.

The 57 and 90 degree operations are summarized in Table 2-7. A great diversity of inclinations make this class of OTV missions. The table shows 27 missions which are accommodated by the OTV, starting in 1997. Preliminary costing indicates that the economic benefits of OTV operations at these inclinations with only 8 missions per year would be marginal and may justify postponing this capability until after 2000.

2.1.3.2 TMS Mission Analysis. The TMS mission model was less well defined and subject to greater uncertainty than the OTV mission model. This is because of the lack of exact definition of the satellites involved in this low energy class. Some satellites will be equipped with their own propulsion systems which will be able to perform some, but not all of the TMS requirement. This capability is difficult to predict and requires a trade study between satellite propulsion and use of the TMS. Satellite servicing requirements in particular require greater examination to establish their frequency and location, whether in-situ or retrieved and serviced at the station.

TMS capability was derived from the ERA 3 TMS in an earlier NASA study. A single stage monopropellant TMS was adopted due to simplicity of operation, low contamination, and ability to meet the mission model requirements for placement, retrieval and service. A gross propellant weight of 5,000 lb, an iginition weight of 7,545 lb and a delivered I_{sp} of 230 seconds was assumed.

Figure 2-3 summarizes TMS missions. It exhibits a 7.5 percent average growth rate resulting from conservative assumptions with respect to mission requirements in the post-1995 time frame. Space station based TMS operations commence in 1992, about one to one and a half years after the station IOC. TMS vehicles may evolve from a shuttle based vehicle designed for compactness to a later generation vehicle designed for ready space maintenance. There is no immediate requirement for the payload/energy capability of the stage to increase, nor is there an early need to evolve to a cryogenic TMS. A requirement for storable propellant will exist on the station either for attitude control and/or satellite ACS replenishment throughout the decade. As shown in Subsection 3.3.3.6, TMS requirements are small compared to cryogens and can be met with orbiter scavenging alone.

2.2 SYSTEM OPERATIONAL REQUIREMENTS

The following subsections describe the operations which must take place on the Space Station to accommodate the selected baseline mission set, and defines the crew and equipment requirements which are needed to support these operations.

Table 2-7. OTV Missions 57 and 90-Degree Operations

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
EMPLACE – 57° – PLANNED	–	–	–	–	–	–	–	–	–	–	–
– UNPLANNED[3]	–	–	–	–	–	–	–	–	–	1/2[1]	–
– 90° – PLANNED	–	–	1	–	–	–	–	–	–	–	–
– UNPLANNED[3]	–	–	–	–	–	–	–	–	1/2[1]	–	1/2[1]
SERVICE – 57° – PLANNED	–	–	–	–	–	–	–	–	–	–	–
– UNPLANNED[3]	–	–	–	–	–	–	–	1	–	1	1
– 90° – PLANNED	–	–	–	–	1/2[1][3]	1[3]	1[3]	1[3]	1[3]	1[3]	–
– UNPLANNED[3]	–	–	–	–	–	1	–	1	1	1	2
RETRIEVE – 57° – PLANNED	–	–	1[3]	–	–	–	–	–	–	1[3]	–
– UNPLANNED[3]	–	–	–	–	–	–	–	–	–	1/2[1]	–
– 90° – PLANNED	–	–	1[3]	–	1/2[1][3]	–	1[3]	–	1[3]	–	2[3]
– UNPLANNED[3]	–	–	–	–	–	–	–	–	1/2[1]	–	1/2[1]
DOD – (ALL 90° EMPLACE)	5	4	3	4	4	2	3	4	3	4	4
SMOOTHING ADJUSTMENT	-1	+1	-1	+1		+1	+1	-1	–	–	–
TOTAL MISSIONS – 57°	–	–	1	–	–	–	–	1	–	3	1
67 TOTAL – 90°	4	5	4	5	5	5	6	5	7	6	9
TOTAL	4	5	5	5	5	5	6	6	7	9	10
TOTAL OTV MISSIONS[2] 27 TOTAL (90° ONLY)	–	–	–	–	–	–	–	1	7	6	9

(1) COMBINED EMPLACE/RETRIEVAL MISSION
(2) ASSUMES 1 OTV OPERATIONAL AT 90° INCLINATION IN 1997 PLANNED MISSIONS FROM DETACHED PAYLOAD SCENARIO REV. C

MAXIMUM 4 PAYLOADS PER MISSION – TWO TANK AEROBRAKED OTV
(3) SINGLE PAYLOAD MISSION – 13 PLANNED MISSIONS AND ALL UNPLANNED MISSIONS (12)

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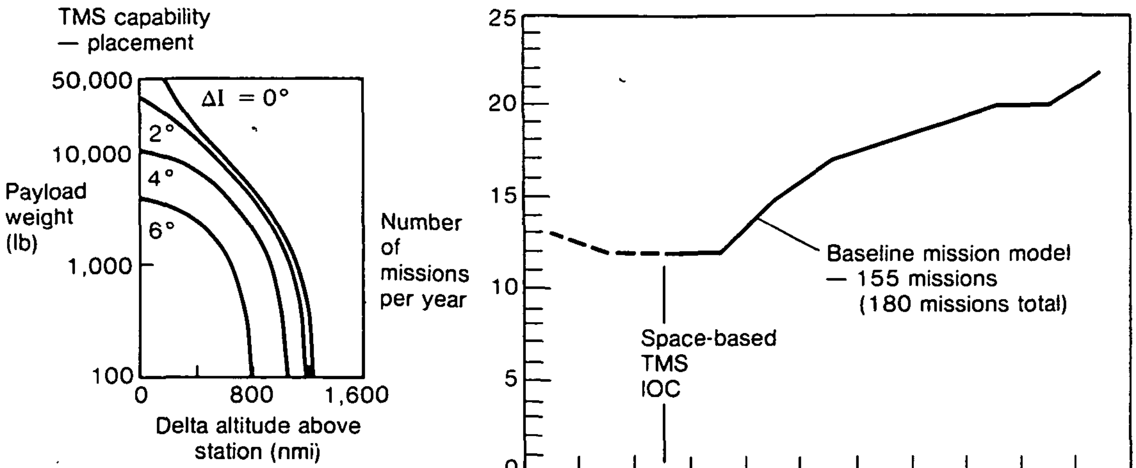

Mission type	90	91	92	93	94	95	96	97	98	99	2000
Placement	(3)	(2)	3	3	3	3	3	3	4	4	5
Retrieval for service	(2)	(2)	2	2	2	2	2	2	2	2	2
Service in-situ	(8)	(7)	5	4	5	6	7	8	9	9	10
ET disposal	—	—	—	—	2	3	3	3	3	3	3
Unscheduled	—	(1)	2	3	3	3	3	3	2	2	2

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Figure 2-3. Space-Station-Based TMS Missions Per Year-
28.5-Degree Operations

A Space-based OTV concept to be used with the Space Station is defined along with its operations plan which emphasizes the servicing operations to be performed on the Station. The OTV servicing equipment required by the Station is identified. The concept, operations, and equipment for a space based TMS is similarly defined. Satellite processing and integration operations are described as part of the OTV and TMS operations. Satellite servicing operations and requirements at the Station are presented in a separate subsection. The processing and integration of payloads to upper stages on the Space Station is described in more detail in a separate subsection. The fifth major operational activity analyzed is the Space Systems Assembly and Construction Operations.

The following four major subsections present the analysis of the crew operations and requirements. The first one, man-operated user accommodations identifies the user requirements to conduct the science and applications missions and describes the analysis we performed to arrive at a recommended crew size. The second subsection, facilities management and housekeeping operations, presents an analysis of requirements for maintaining the Space Station. Operational activities analysis covers the analytical approach that was used to arrive at the crew size and equipment for the Space Station servicing operations. The final subsection pertains to the crew. The crew and equipment requirements are identified including the crew tasks and capabilities, crew timelines, crew IVA/EVA equipment, and the automated tasks and elements.

The last subsection discusses the operational floor plans for the Space Station and determines the arrangement of equipment and facilities needed to perform the overall crew operations efficiently with minimum equipment.

2.2.1 OTV CONCEPT AND OPERATIONS. A baseline Orbital Transfer Vehicle concept is presented here which was used to develop operations accommodations concepts. This concept is for an advanced OTV designed specifically for the space environment and on-orbit maintenance. Features of this concept peculiarly adaptable to a space-based vehicle, are summarized as follows:

- Lightweight Spherical Propellant Tanks
- Modular Tankage Arrangements for Mission Flexibility
- Fixed Aerobrake
- Lightweight Open Truss Structure
- Universal Payload Interface Module
- Quick Changeout Astrionics, ACS, Propellant Feed and Main Engine Modules
- Fixed High Area Ratio Engine Nozzles

The baseline OTV is designed to be carried to the Space Station in a disassembled state on a single dedicated shuttle flight. After assembly and initial checkout at the base the OTV is used primarily in a recoverable mode to deliver and/or retrieve payloads from GEO or HEO and to return to the Space Station after each mission for maintenance and payload integration. Occasional planetary escape missions may call for flight profiles from which the OTV would not be recovered.

2.2.1.1 OTV Concept. The basic vehicle concept is illustrated in Figure 2-4. The OTV is comprised of modular elements to simplify logistics, maintenance and reconfiguration for different missions. The OTV is built around a central core section to which cryogenic propellant (H_2/O_2) tanks are attached, along with an aerobrake, a main engine and an astrionics/docking module. Different combinations of these elements can satisfy a wide variety of missions needs, such as:

a. Payload delivery, servicing or retrieval

b. Low thrust ($\sim$.025g), high thrust ($\sim$.4g) or dual redundant thrust ($\sim$.08g)

c. Recoverable or expendable

d. Two tank or four tank module arrangements for various payload weights.

e. Satellite payloads or Manned Mission Module

f. Aerobraked or All Propulsive

Figure 2-5 illustrates the four tank module version of the OTV. Propellant capacity is doubled to 27,900 kg from 13,950 kg, and payload mass carrying capability is increased by 160 percent. The fixed aerobrake (Figure 2-4) can also be attached to this vehicle.

The core section is a truss beam which supports subsystems plumbing, disconnects, astrionics, berthing interfaces, a payload interface, and attitude control thrusters. This core section is the primary structure of the vehicle with provisions to allow quick changeout of components such as the tanks, engine(s), and astrionics packages.

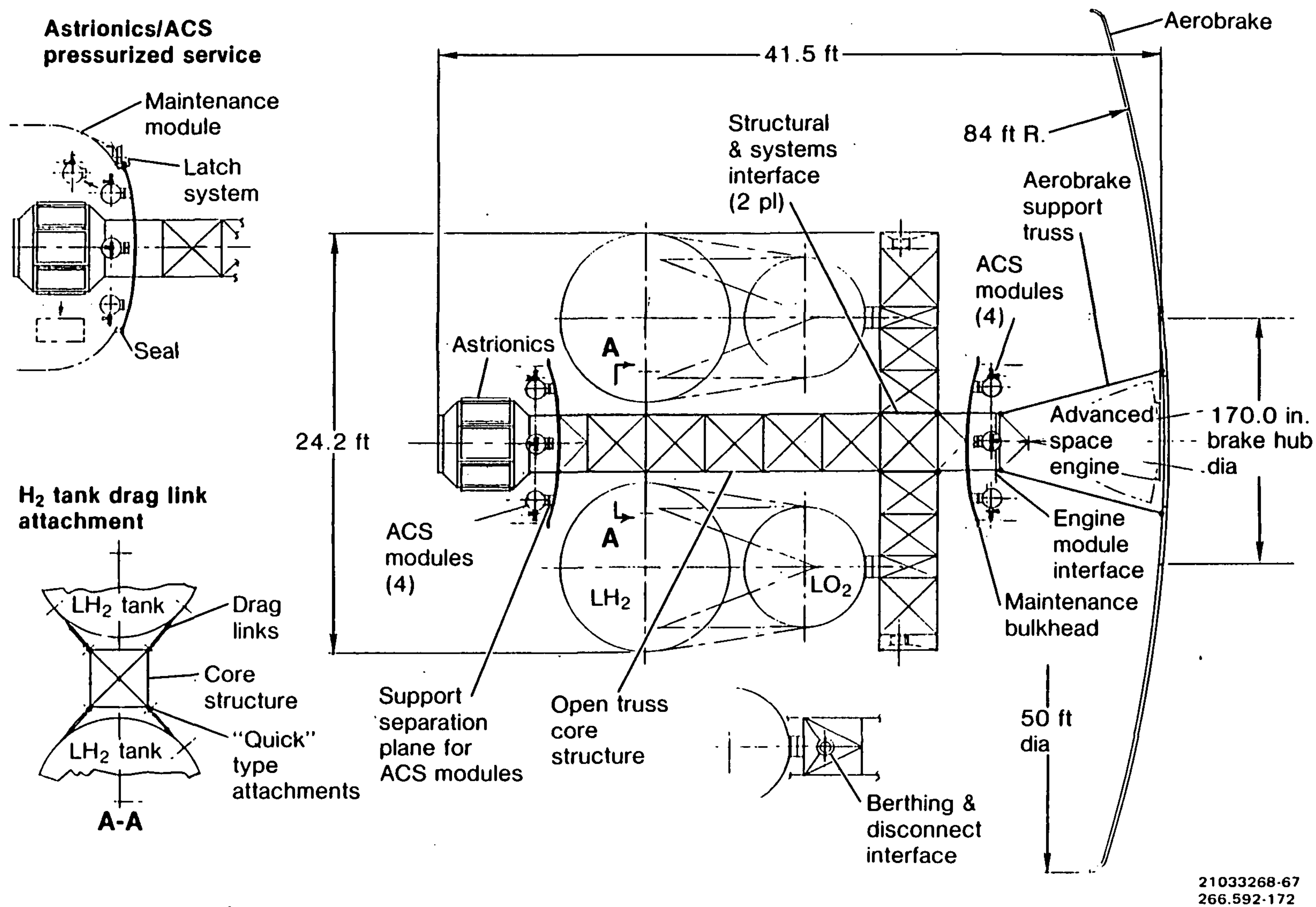

Figure 2-4. Two-Tank Aerobraked Space-Based OTV

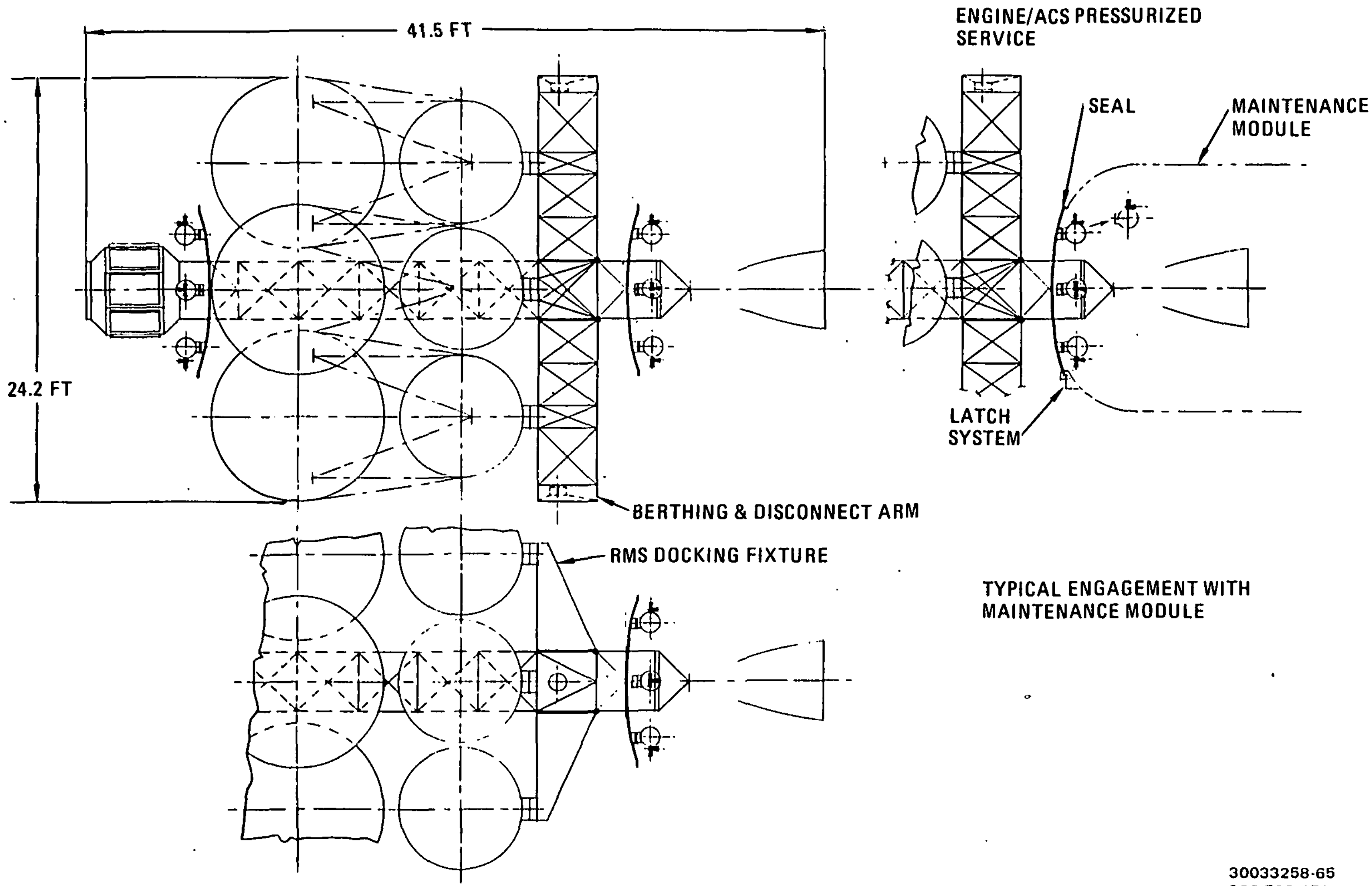

Figure 2-5. Four-Tank, All Propulsive Space-Based OTV

High maintenance items, such as the main engine(s), ACS thruster quads, astrionics, and docking assembly are located at the ends of the vehicle where they are easily accessible. With a relatively minor weight penalty, the ends of the vehicle could be fitted with a pressure wall allowing the OTV to dock to a pressurized service bay with either of the ends within the bay, allowing access to critical components of the OTV in a shirtsleeve environment.

The propellant tanks are attached to the core section with cantilever trusses. The trusses are fixed to the tanks and interface with the core section through a systems disconnect panel and structural attachments. These cantilever trusses provide a means for supporting and handling the tanks during Shuttle transportation as shown in Figure 2-6.

The fuel tanks are supported from the oxidizer tanks with a truss system. One complete tank module is composed of an oxidizer tank, a fuel tank, an interconnecting truss and the cantilever truss which is mated to the core section. The truss members between the tanks are oriented such that the centerlines are tangent to the tank shells. The fuel tanks are equipped with drag struts at the forward ends for lateral support and disconnection from the core section; and as a holding device during storage. A retractable disconnect panel on the core section actuates to engage the disconnect fittings.

The aerobrake is supported from the core section with a conical truss structure and is equipped with two doors for covering the engine opening. An alternate procedure would delete these doors and run the engine at low idle mode during atmospheric braking.

The forward end of the core section is equipped with an octagon structure called the astrionics module which houses the astrionic packages and provides an interface for the payload. The astrionics packages can be quickly disconnected from this module for maintenance in a shirtsleeve space station module or for return to earth.

The aft end of the core module has an interface panel for the engine package. This interface panel contains disconnects for all the engine fluid and electrical lines and also contains a structural latch system for securing the engine package to the core section. A typical engine package consists of a flat interface panel with disconnects, a thrust cone, a set of gimbal lines, and a thrust vector control system. This package contains all engine systems and is designed to plug onto the core section as a single package.

Four attitude control system (ACS) modules are located aft of the astrionics module and forward of the main engine. Each of the ACS modules are complete self-contained units consisting of a spherical tank, an acquisition system, a cluster of thrusters, electrical wiring harnesses (with a disconnect) and an interface boss for quick type connection to the core section. The propellant is hydrazine. Prior to installation the tanks are charged with propellant, pressurized, and locked up.

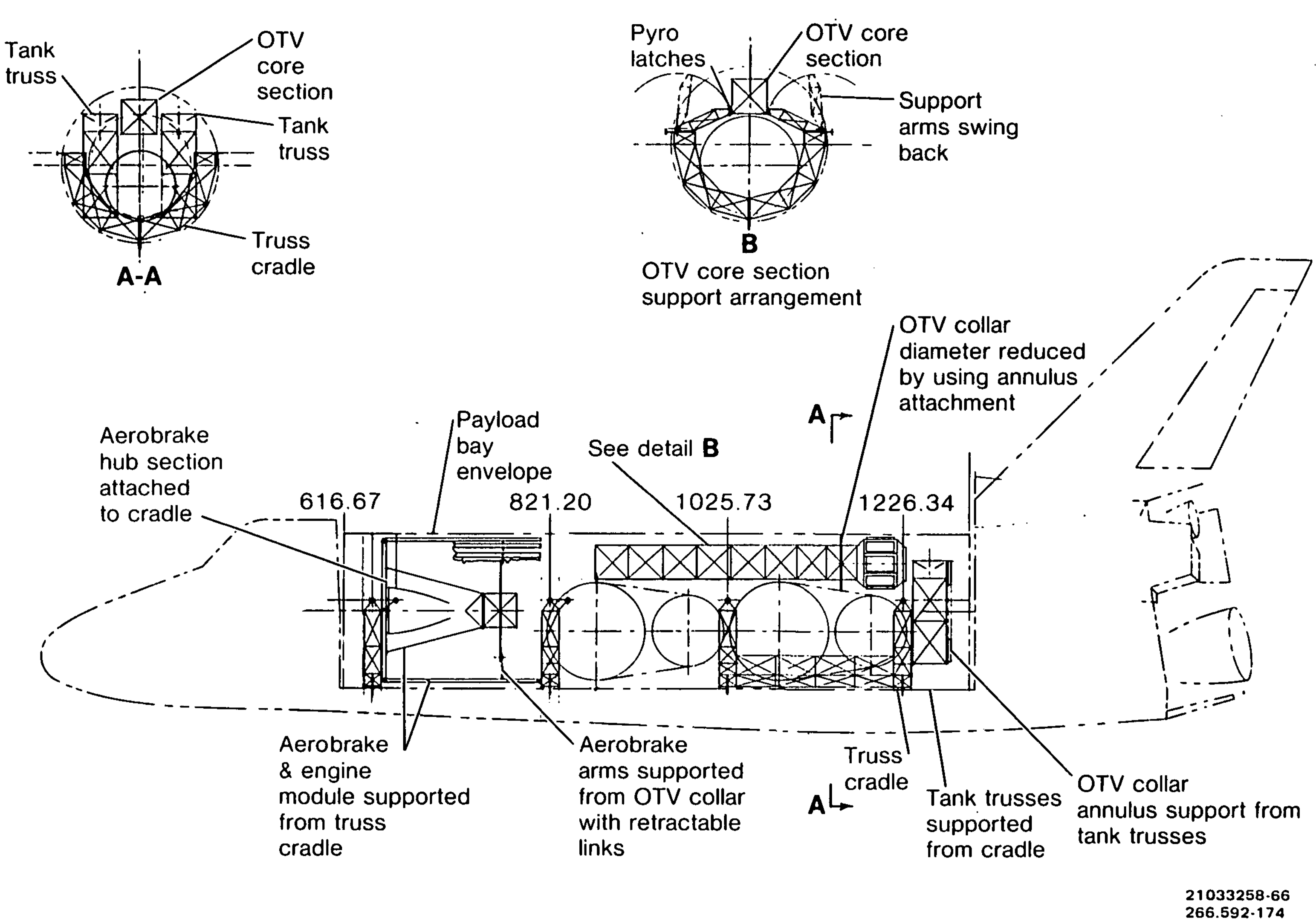

Figure 2-6. Two-Tank Aerobraked OTV Disassembled for Shuttle Carriage

An alternate ACS system which maximizes performance and reduces the number of propellants which must be provided at the station is a two gas (or two liquid) LOX/H_2 ACS system drawing propellant from a start basket in the main tanks.

A third possibility under consideration is an ACS system which uses hydrogen gas. Slugs of liquid hydrogen are taken from the main tanks and injected into a hot flash tank which in turn feeds the thrusters. This alternate ACS system will require a slug pump, interconnecting plumbing and a pressure control system. The thrusters would be modularized for simple, one-step, plug-in type replacement.

Table 2-8 details the OTV weights. Note that these weights are for a clean sheet, all-up design which is designed exclusively for operation in space. Advanced composites for the truss structures and advanced metal forming procedures for the propellant tanks are assumed. The propellant tanks and structure are designed to support a full propellant load at vehicle accelerations of 1.2 gs or less (for maximum weight efficiency they cannot carry propellants during a Shuttle delivery flight).

2.2.1.2 OTV Engine Characteristics. The Advanced Space Engine integrated into this concept is specifically designed for extended operation and on-orbit maintenance as well as high performance. The weights and performance data in Table 2-9 are derived from Rocketdyne data generated in an earlier contract.

The engine may be modified for low thrust with a ground installed kit fitted to the nozzle throat coupled with altered propellant feed system adjustments to allow it to operate for long periods in pumped idle mode. This modification allows the engine to operate at 10 percent nominal thrust at a slightly lower Isp $\sim$465-470 sec.

The man rated OTV, not illustrated, may be configured with dual main engines for redundancy. Previous internal studies have concluded, however, that safety and redundancy issues are better resolved with a separate propulsion system removed physically from the main engine. Most failure modes for the main engine will also result in the loss of a second engine located adjacent to it. An augmented ACS which is capable of generating appreciable vehicle acceleration ($>$0.01g) with reasonable performance (Isp$>$400) may fulfill abort criteria better and at a lower overall weight than a dual engine arrangement.

2.2.1.3 OTV Performance. The OTV baseline is designed to meet all requirements of the MSFC Nominal Mission Model, Rev. 6 October 1982. The two tank aerobraked OTV (Figure 2-4) and four tank aerobraked OTV (Figure 2-5 with an aerobrake) performance capabilities are summarized in Table 2-10. Total propellant required includes unusable residuals, boiloff losses, start up and shut down losses and Attitude Control System propellant as well as usable main impulse propellant. A gaseous O_2/H_2 ACS is assumed.

Table 2-8. Preliminary Weight Summary

a. Core Assembly	(lb)		
Propulsion System Group	640		
Flight Control Group	230		
Fluid System Group	150		
Electrical Group	70		
Guidance & Navigation	60		
Communications & Control	70		
Docking Subsystem	140		
Primary structure	240		
Contingency	240		
Core Assy Inert Wt	1,840		
Auxiliary Propellant	60		
Core Assy All-Up Wt.-All Propulsive	1,900		
Aerobrake	1,690		
Core Assy All-Up Wt.-Aerobraked	3,590		
b. Tank Assembly		2 Tanks (lb)	4 Tanks (lb)
Basic Structure		400	800
Secondary Structure		110	220
Insulation		100	200
Propellant, Pressurization & Electrical Group		100	200
Contingency		110	220
Tank Inert Wt.		820	1,640
c. Propellant (O_2/H_2 @ 6:1)			
Unusable + Losses		140	280
Usable		28,400	56,800
Stage at Propellant Depletion-All Propulsive		2,860	3,820
-Aerobraked		4,550	5,510
Stage at Launch -All Propulsive		31,260	60,620
-Aerobraked		32,950	62,310

The two tank and four tank all-propulsive OTV baselines performance capabilities are summarized in Table 2-11. The relatively high propellant mass fraction of the all-propulsive vehicle reduces the performance gain for the aerobraked version on the deliver payload mission. The aerobrake offers a significant payload advantage for the payload retrieval (manned mission and GEO satellite servicing are examples) mission.

Table 2-9. Advanced Space Engine Characteristics

		Advanced Space Engine - Baseline -
Thrust	(lb_F)	10,000
Chamber Pressure	(psi)	1,610
Area Ratio		625:1
Mixture Ratio	(O_2/H_2)	6:1
Specific Impulse	(sec.)	482.5
Length	(in.)	~94
Maximum Diameter	(in.)	~53
Dry Weight	(lb_F)	~290
Prop. Flow Rate	$\frac{(\text{lb Prop.})}{(lb_{THRUST} \times sec)}$	$2.073\ 10^{-3}$

Table 2-10. Aerobraked OTV Performance Summary*

	Payload To GEO (lb)	Payload Return (lb)	Total Prop. Required (lb)	GLOW (lb)
Two Tank - Payload Delivery	11,000	-0-	28,600	43,950
- Return Payload	5,880	5,880	28,600	38,830
Four Tank - Payload Delivery	28,700	-0-	57,140	91,010
- Return Payload	15,360	15,360	57,140	77,670

*Maximum Capability in each mode

Figure 2-7 plots total propellant required versus payload delivered to GEO. Straight lines indicate payload delivery cability for partial propellant loads. Solid lines are aerobraked vehicles and the segmented lines are for all-propulsive vehicles. The reusable lines indicate standard payload-delivered-to-GEO-stage-returns-empty operation. Expendable operation includes placing the spend stage in a debris orbit 2000 nmi above GEO. The Reusable Round Trip Payload mission assumes equal payload up and back.

Table 2-11. All Propulsive OTV Performance Summary*

	Payload To GEO (lb)	Payload Return (lb)	Total Prop. Required (lb)	GLOW (lb)
Two Tank - Payload Delivery	9,610	-0-	28,600	40,870
- Return Payload	2,780	2,780	28,600	34,040
- Expendable	16,500	-0-	28,600	47,760
Four Tank - Payload Delivery	25,800	-0-	57,140	86,420
- Return Payload	7,460	7,460	57,140	68,080
- Expendable	35,000	-0-	57,140	95,620

*Maximum Capability in each mode

The all-propulsive vehicle delivers 11 percent less payload than the aerobraked vehicle on the standard deliver payload mission. On the return payload mission the all-propulsive vehicle delivers less than half the payload of the aerobraked vehicle.

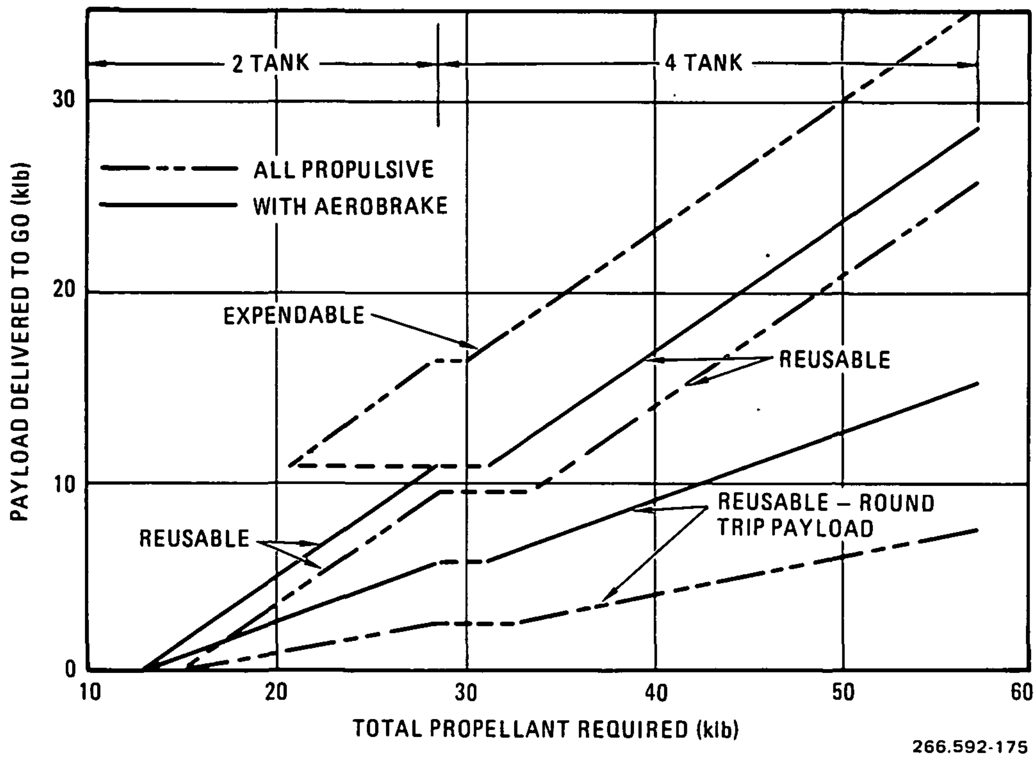

Figure 2-7. Baseline Space-Based OTV Payload Capability

Figure 2-8 plots payload returned to LEO versus payload delivered to GEO. At the extremes, the points along the vertical axis correspond to the standard payload delivery mission tabulated in Tables 2-10 and 2-11 while the points along the horizontal axis depicts a mission where the OTV ascends to GEO with a full propellant load, retrieves a satellite, and returns it to LEO. The dashed line at 45 degrees indicates the return payload mission where payload delivered to GEO is returned to LEO. The all-propulsive vehicle is severely penalized on the satellite retrieval mission, returning less than one-third the payload of the aerobraked vehicle.

2.2.1.4 Space-Based OTV Operations. The basic space-based OTV operations are presented in Figure 2-9. The OTV is delivered to the Space Station by Shuttle and assembled there as described in Subsection 2.2.1.4.1. The vehicle is then mated with a payload and prepared for launch as outlined in Subsection 2.2.4. The OTV performs the mission of orbital payload (satellite) delivery, on-orbit servicing or other mission-oriented tasks and returns to the Station for maintenance, which includes the process of servicing. The vehicle is retrieved and maintenance is performed in preparation for the next mission as stated in Subsection 2.2.1.4.2. In the operations described in this section the OTV performs a satellite delivery mission. Mission scenarios also include satellite servicing, which requires integration with a payload module. The payload module would either be a manned module or an unmanned servicing module which contain the appropriate servicing equipment.

2.2.1.4.1 OTV initial delivery and assembly. The space-based OTV will be loaded into the Shuttle Orbiter cargo bay and transported to the Space Station as separate major components to be assembled at the Station (Figure 2-6). The

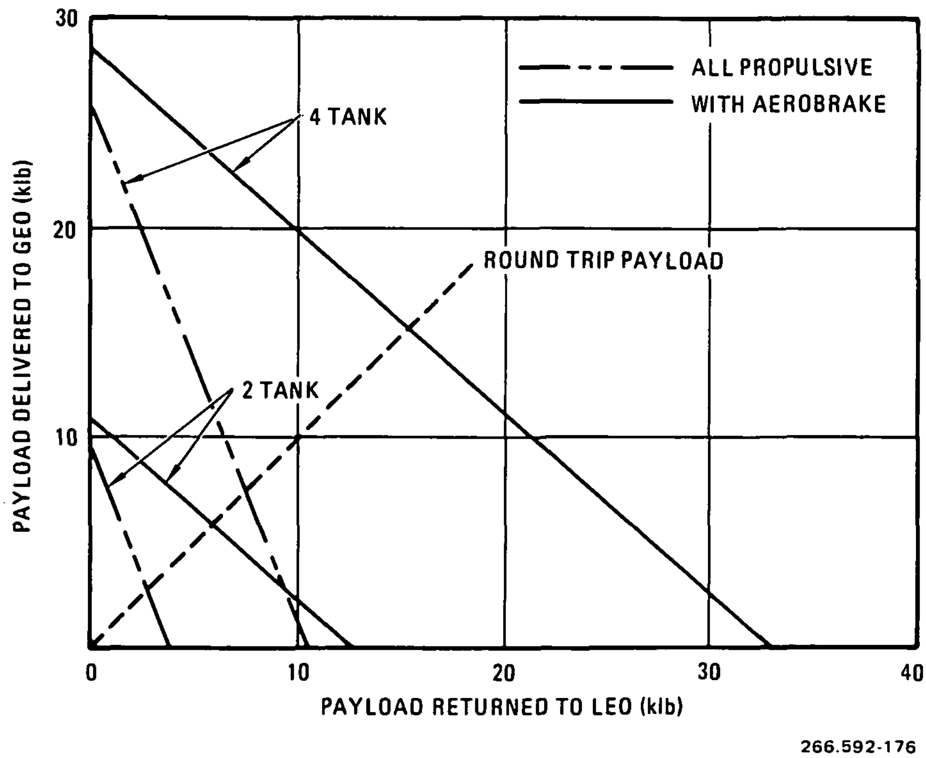

Figure 2-8. Sortie Mission-Return Satellite Payload Capability

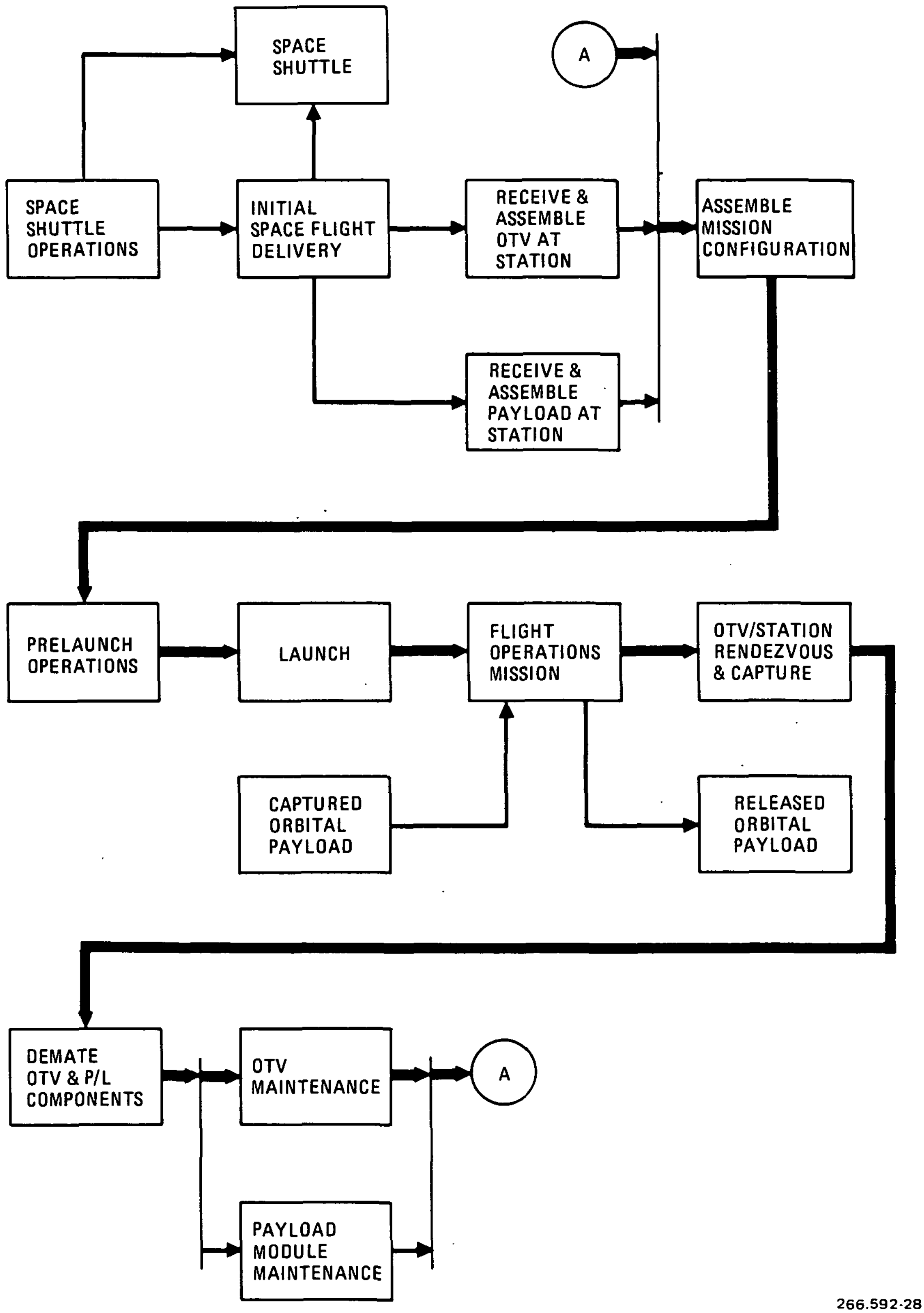

Figure 2-9. Spaced-Based OTV Operations

major OTV components consist of the core section, tank trusses, tank modules, and engine/aerobrake. The core section configuration includes the main truss structure with all avionics installed, along with the attitude control system. The core section is offloaded first and is removed from the Shuttle with the maintenance dock Remote Manipulation System (RMS). The RMS holds the core section in place on station to allow further assembly. The Shuttle RMS is activated and used to offload the tank truss. The tank trusses are positioned on the core section with the Shuttle RMS. They are assembled to the core section, along with the forward collar annulus, with EVA assistance. The dock RMS then places the assembled core section in the maintenance dock after a thorough television inspection of the berthing interfaces. The OTV core section is installed vertically with respect to the maintenance dock structure. The interface is locked and the core section is then rotated 90 degrees to line up with the maintenance dock. The tank modules and engine/aerobrake are transferred to the maintenance dock and inspected in a similar manner. The tank modules are positioned for mating with the core section, one at a time. The RMS is then deactivated and locked as a safety precaution, while EVA personnel secure the tank modules to the tank truss core structure. EVA personnel retreat to a safe area as the RMS is activated and released.

The engine/aerobrake assembly is the final component to be installed on the OTV. It is positioned and secured by EVA personnel following the same process. The aerobrake latches to the dock truss beams and the shield disconnects from the aerobrake support truss. The RMS is then stowed and the OTV assembly receives a complete EVA visual inspection before the EVA personnel enter the airlock to perform post-EVA operations.

The OTV is subjected to systems operational testing to verify its flight readiness status. If a problem is detected, the operation reverts to the unscheduled corrective maintenance scheme outlined in Subsection 2.2.1.4.2 and Figure 2-10. When the OTV achieves operational status the sequence of events progress toward payload integration activities.

The OTV is placed in a storage condition when it is not required for immediate mission operations. The storage condition is attained by extending the shelter to cover the unfueled OTV and deactivating all vehicle systems.

Figure 2-11 depicts the major OTV delivery and assembly operation process, and Figure 2-12 follows a more detailed functional flow of the same process.

2.2.1.4.2 <u>OTV retrieval and maintenance</u>. The maintenance concept for the OTV is based on a three-level maintenance scheme. Level I maintenance consists of scheduled and unscheduled activities that occur while the vehicle is berthed in the Space Station maintenance dock. Scheduled maintenance encompasses handling, assembling, servicing, inspection, checkout and some time-related remove and replace tasks, such as an engine changeout. Unscheduled repair tasks will primarily involve removal and replacement of failed components. The modular design of the OTV lends itself to these remove and replace activities, thereby enhancing maintainability of the vehicle. The Level II category encompasses replaceable units that can be taken into the Station and repaired within the shirtsleeve environment. Units that cannot be repaired at the Station are returned to earth for Level III maintenance. The OTV corrective maintenance functional flow diagram in Figure 2-13 outlines these

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Figure 2-10. OTV Retrieval and Maintenance Operations Flow

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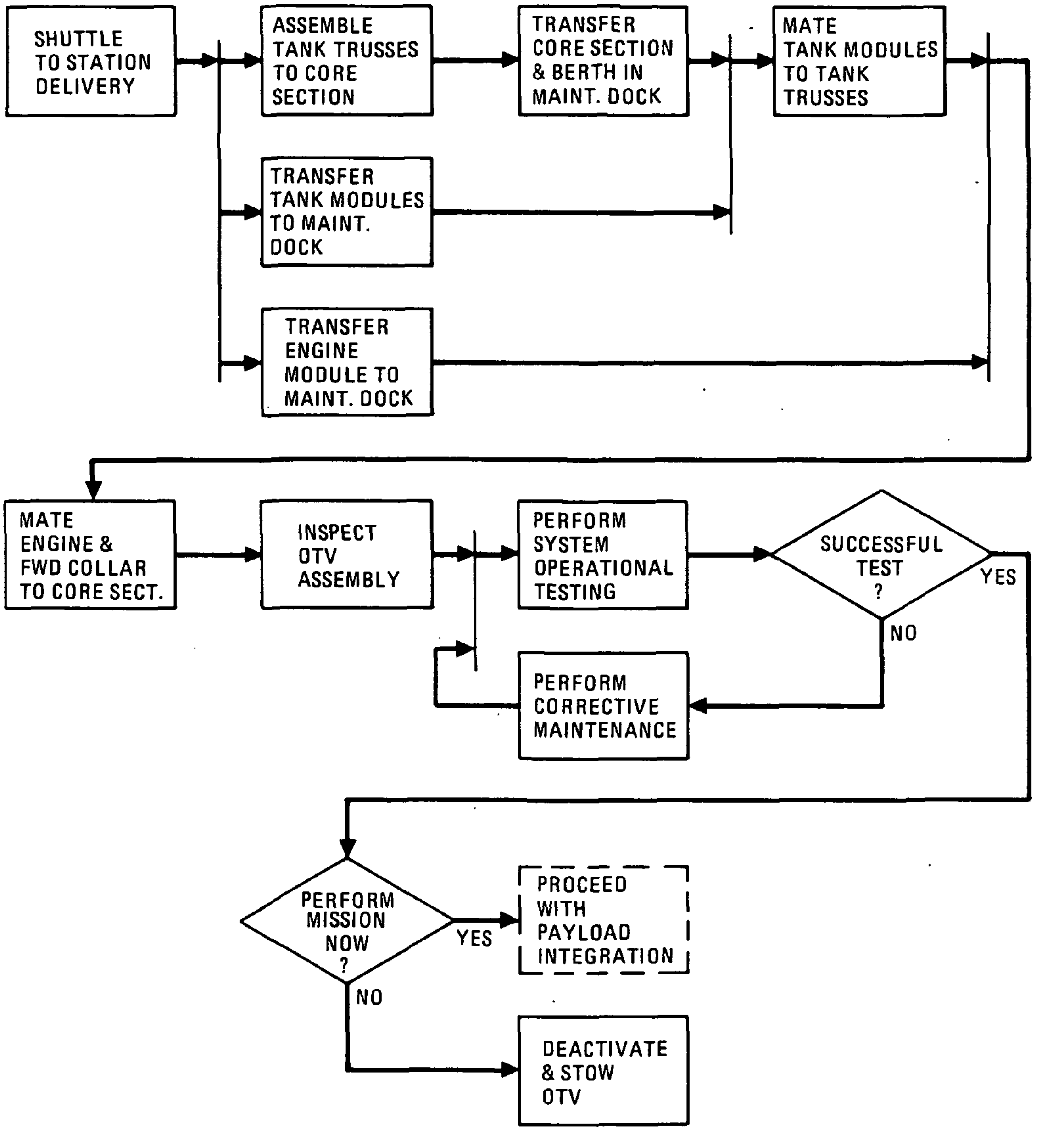

Figure 2-11. OTV Delivery & Assembly Operations

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Figure 2-12. Initial OTV Space Station Delivery and Assembly Operations Flow

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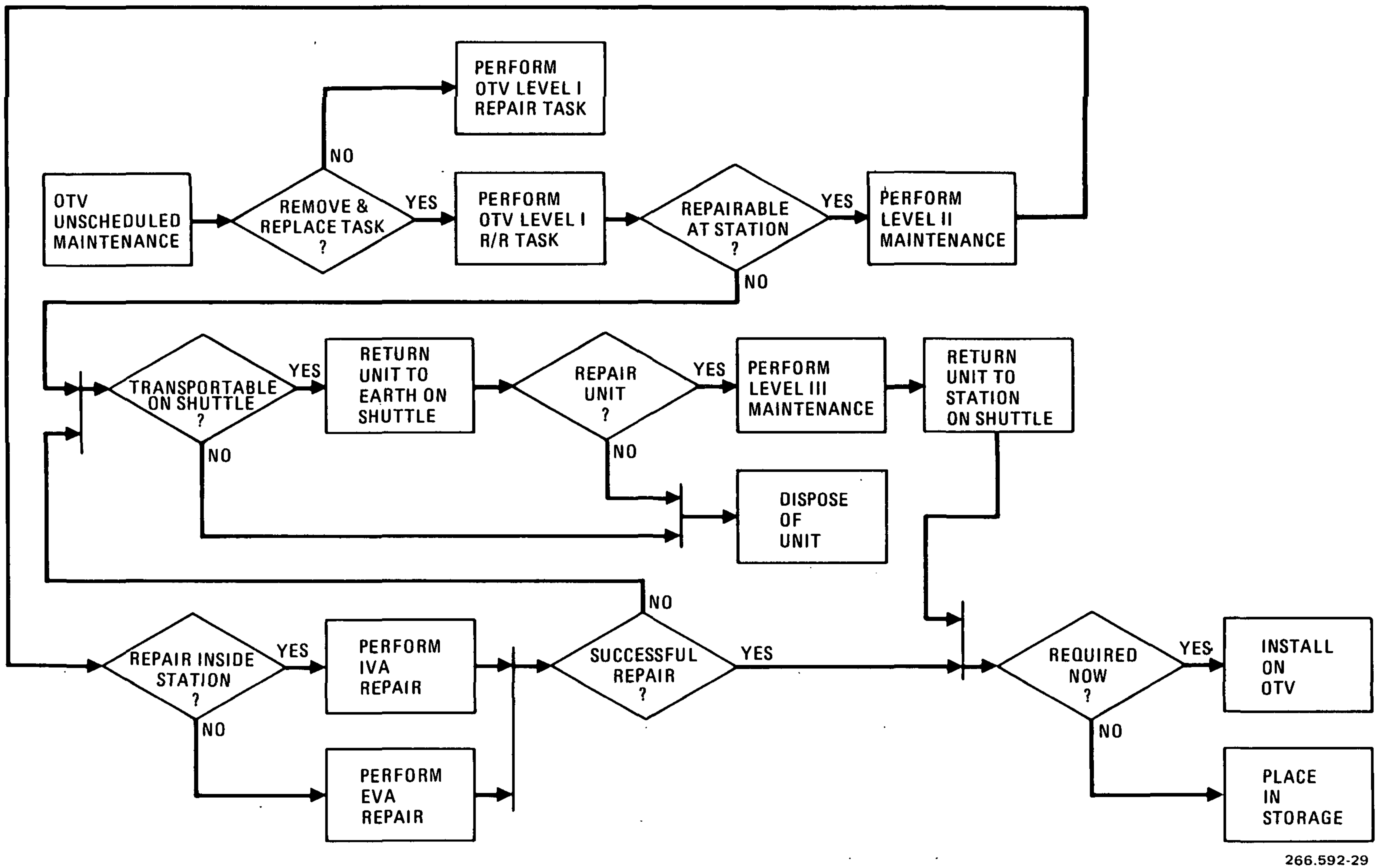


Figure 2-13. OTV Corrective Maintenance Functional Flow

these level of maintenance activities. The major OTV maintenance operations are presented in Figure 2-14 and a more detailed diagram which also includes a typical OTV retrieval operation along with the maintenance process can be found in Figure 2-10.

Two methods for retrieval of the OTV have been defined. One method requires the OTV to rendezvous and dock with a Station docking arm, which then guides the vehicle into the maintenance dock. The other method, which is outlined in the diagrams, only requires the OTV to rendezvous within reach of the RMS. The RMS grasps and positions the OTV, pausing for visual inspection, and then inserts the vehicle in the maintenance dock in a vertical position with respect to the dock structure. The berthing interfaces are engaged and their integrity verified as the RMS is released, retracted, and stowed. The OTV is rotated 90 degrees in line with the maintenance dock and the shelter is extended to cover the OTV. Propellant leak checks are performed on the vehicle and propellant transfer system. The transfer lines undergo a chilldown process, then propellant is transferred from the vehicle to the Station storage tanks. A refrigeration unit and shielding maintain the proper propellant temperatures. Visual inspection is performed on the vehicle with a television camera and monitor systems. EVA inspection is limited to occur only in conjunction with remove and replace tasks or when special damage assessment is required. While visual inspection is being accomplished, the vehicle computer-controlled fault detection system is scrutinized for fault identifications and the results are recorded for maintenance planning. Faults are verified by performing an operational test of the system. The fault is then isolated to the replaceable unit by activating the built-in test capability. Built-in test is an important feature, because it minimizes the OTV to Station interface and Station equipment diagnostic requirements.

The unscheduled maintenance tasks are integrated into a complete schedule and unscheduled maintenance plan. Many of the OTV avionic components can be removed and replaced within the maintenance module shirtsleeve environment. The engine may also be repaired or replaced within this same environment, once it has been determined free of residual propellants and is safe to enter. Components that may require EVA operations for remove and replace tasks are the main engine, when not safe for module entry, tank modules and core section. A typical engine EVA remove and replace task is presented in Figure 2-15.

With the completion of corrective maintenance activities, the vehicle receives a final operational checkout which validates that the OTV is ready for payload integration and mission operations.

2.2.1.4.3 Facilities and support equipment requirements. The major Space Station facilities and equipment required to support a space based OTV operation are contained in Figure 2-16, and a corresponding concept of the basic maintenance facilities, related equipment, and operations are shown in Figures 2-17, 2-18 and 2-19.

The identified Space Station assets for accommodation of a space based OTV are listed in Table 2-12.

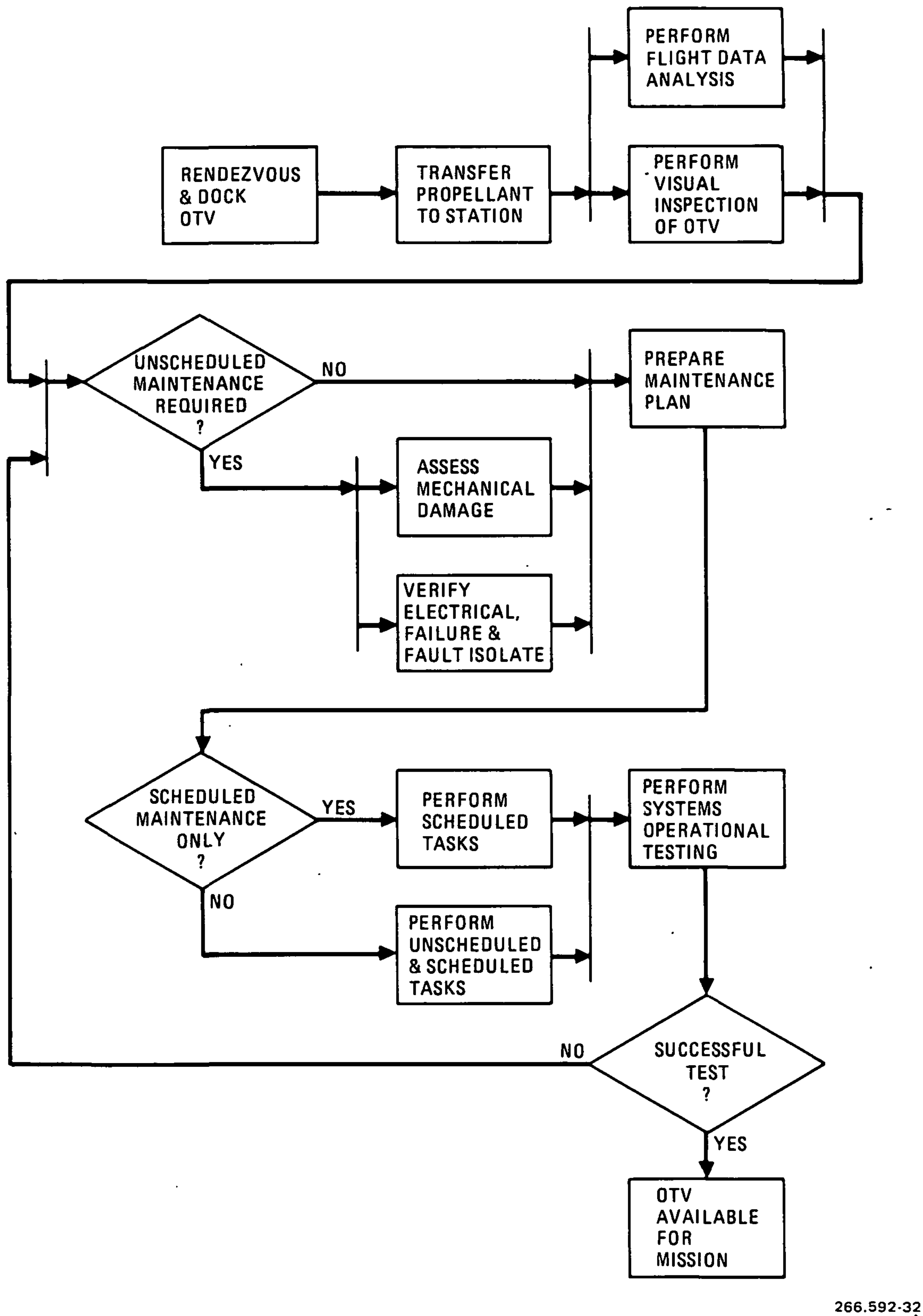


Figure 2-14. OTV Maintenance Operations

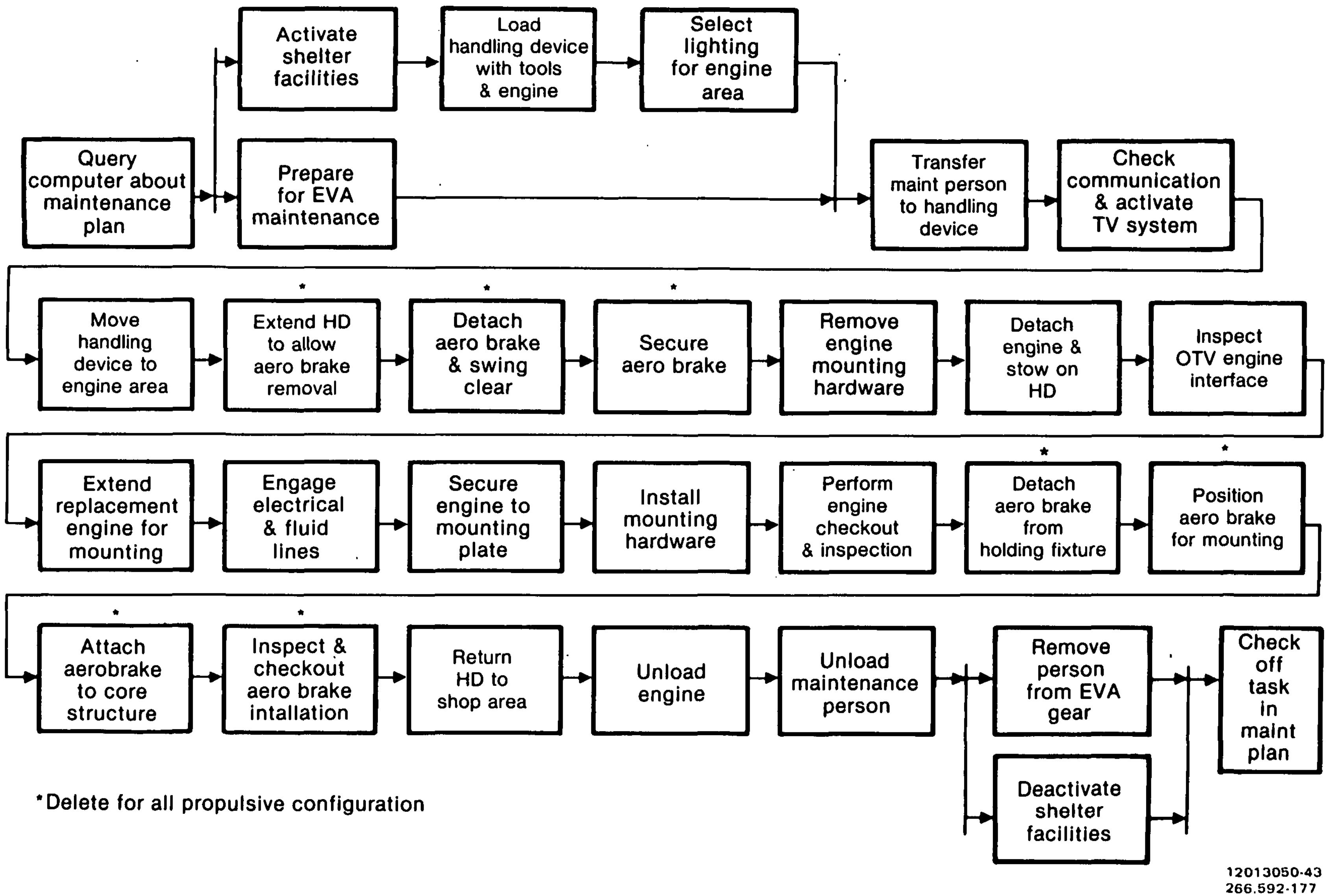


Figure 2-15. Remove and Replace Engine-EVA Operation

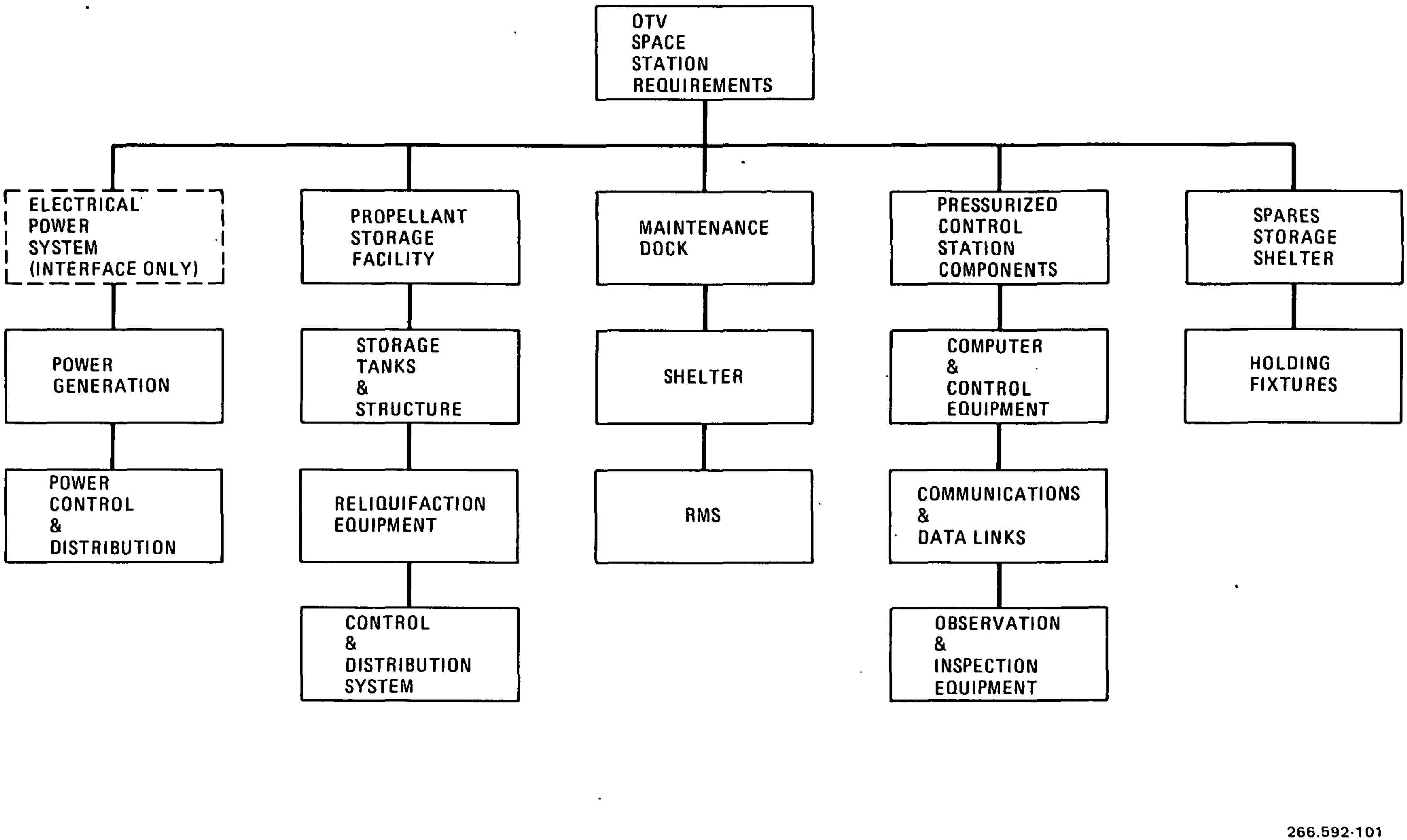
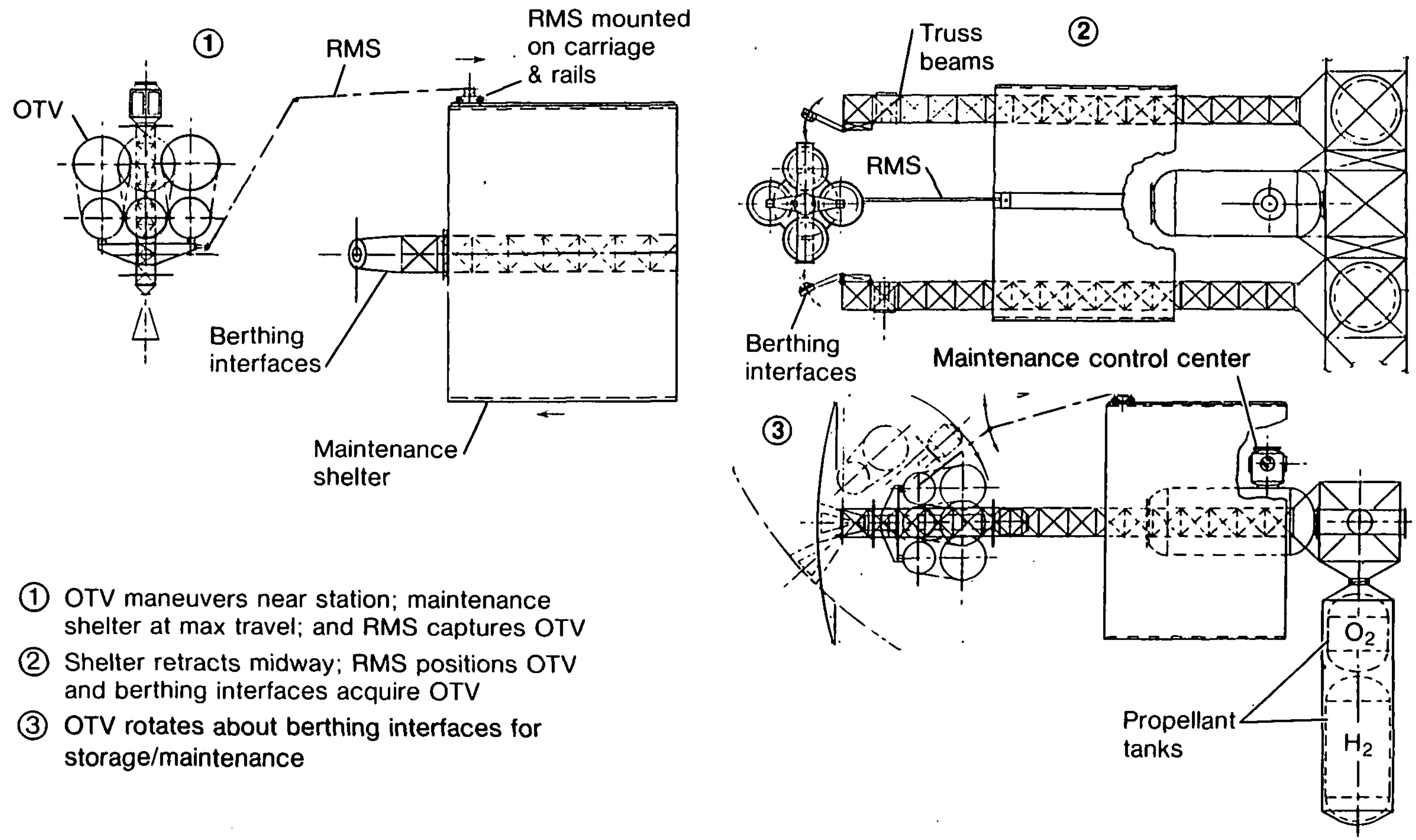


Figure 2-16. Major Space Station Facilities and Equipment Required to Support OTV



① OTV maneuvers near station; maintenance shelter at max travel; and RMS captures OTV

② Shelter retracts midway; RMS positions OTV and berthing interfaces acquire OTV

③ OTV rotates about berthing interfaces for storage/maintenance

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Figure 2-17. Space-Based OTV Capture & Berthing Concept

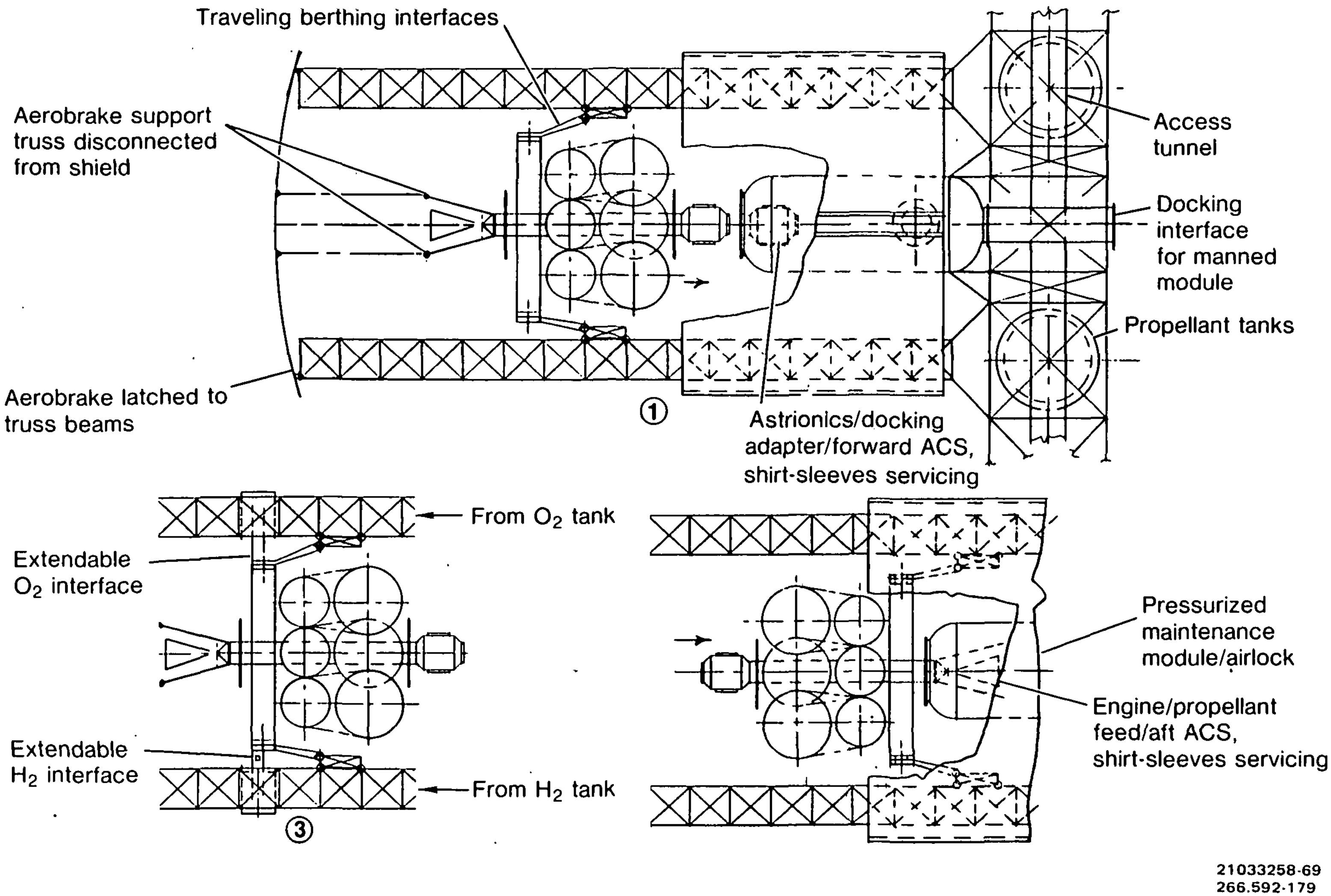

Figure 2-18. Space-Based OTV Service & Propellant Loading Concept

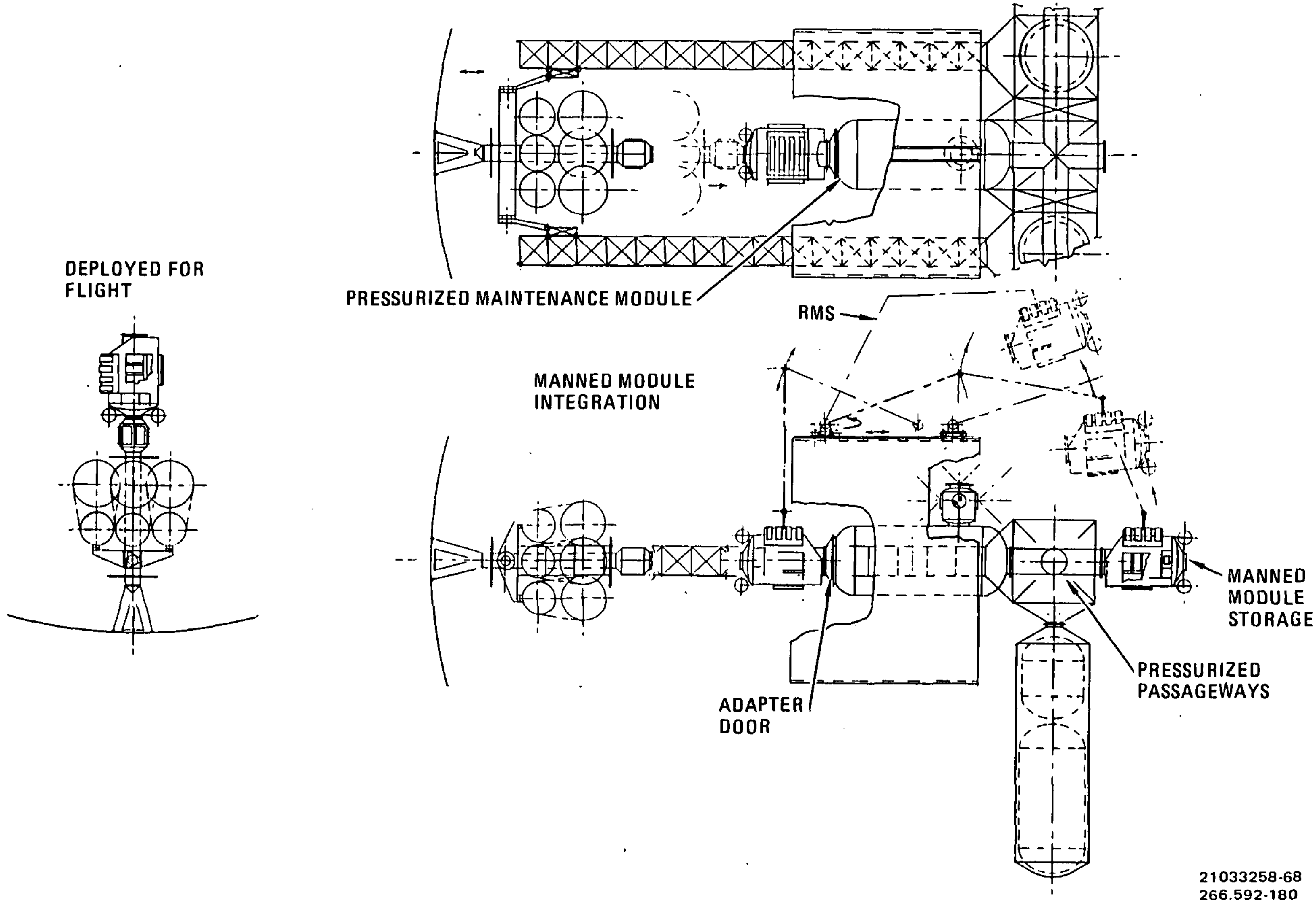

Figure 2-19. Manned Mission Module Storage Integration & Deployment Concept

Table 2-12. Space Station OTV Element Breakdown

- MAINTENANCE DOCK
  - -- Main Truss Support Structure
  - -- OTV Berthing Interface, Structure, Rotating Mechanism, and Carriage
  - -- Electrical Interconnects Between Berthing Interface, Maintenance Module, and Power Source Interface
  - -- Fluid Lines from Quick Disconnect Panel to Propellant Storage Control Interface
  - -- Support Structures for Shelter
  - -- Rail/Track System for Shelter and Berthing Carriage
  - -- Electrical Interconnects Between Shelter Interface, Maintenance Module, and Power Source Interface
- MAINTENANCE SHELTER
  - -- Main Shelter Structure
  - -- Shelter to Maintenance Dock Structure Rail/Track Interface
  - -- Shelter Mobility Control Motors
  - -- Lighting Installation
  - -- Electrical Interconnects Between Lights and Maintenance Dock Interface
  - -- Spare Parts Storage Compartments or Holding Fixtures on Interior Shelter Walls to Contain Avionics, ACS Module Spares and Possibly an Engine
  - -- Handling Device to Provide EVA Mobility and Restraint, Equipped with TV System and Communications; RMS/Robotic Capability
  - -- Electrical Interconnects Between Handling Device and Maintenance Dock Interface
  - -- Exterior RMS Support with Rails/Tracks
  - -- RMS Including TV, Lights, End Effector/Tool Adapter
  - -- Electrical Interconnects from RMS to Maintenance Dock Interface
  - -- Tools Storage Fixture for Handling Device/Robotics and RMS
  - -- Possible Antenna Installations

Table 2-12. Space Station OTV Element Breakdown, Contd

- PROPELLANT STORAGE
  - -- Main Support Structure
  - -- Hydrogen Storage Tank
  - -- Oxygen Storage Tank
  - -- Control and Interface Unit, Valves, Controls, etc.
  - -- Fluid Lines from Tanks to Control Interface
  - -- Refrigeration Unit and Plumbing
  - -- Electrical Interconnects Between Control Unit, Refrigeration Unit, Maintenance Module and Power Source
  - -- Radiators
- MAINTENANCE MODULE
  - -- Pressurized Compartment
  - -- Airlock for EVA Operations (Serves as Observation Module)
  - -- Airlock and OTV Interface
  - -- General Purpose Computer System
  - -- Dedicated Control Equipment
  - -- Communications and Data Links
  - -- Observation and Inspection Equipment Monitors (Include TV, Propellant Sensors)
- SPARES STORAGE SHELTER
  - -- Holding Fixtures
  - -- Lights
- ELECTRICAL POWER SYSTEM (MAIN STATION ASSET)
  - -- Power Generation System
  - -- Power Control and Distribution System
  - -- Maintenance Facility Interface

2.2.2 TMS CONCEPT AND OPERATIONS. The Teleoperator Maneuvering System (TMS) is conceived as a small space transfer system used to service space missions. Its original development was performed to enhance the Shuttle Transportation System and it has obvious application for operation in an early space station system.

2.2.2.1 Baseline TMS Description. The baseline Shuttle compatible TMS design philosophy takes a building block approach providing a basic core vehicle with propulsive, communication and servicing kit add-ons to provide for evolving mission needs and minimize costs. It has a multipurpose capability to enhance and augment the STS by providing flexibility in payload delivery and support operations. Its small size minimizes weight and length, thereby impacting Shuttle payload bay volume as little as possible. A mix of autonomous and man-in-the-loop control in the orbiter and appropriate ground or space stations for periodic or real time control provides significant control flexibility. The standardization of TMS/payload interfaces is a goal to minimize system complexity. It is designed to the safety aspects of the man-rated Shuttle and to avoid STS and payload contamination. A goal of a ten-year life with limited refurbishment and maximum use of developed hardware provides a cost effective TMS and reduces user costs. The Shuttle compatible TMS with potential add-ons is a Space Station servicing and mission enhancement system.

The baseline TMS shown in Figure 2-20 has a diameter of 156 inches, compatible with the Shuttle payload bay and a length of 37 inches to minimize its impact on payload length allowables.

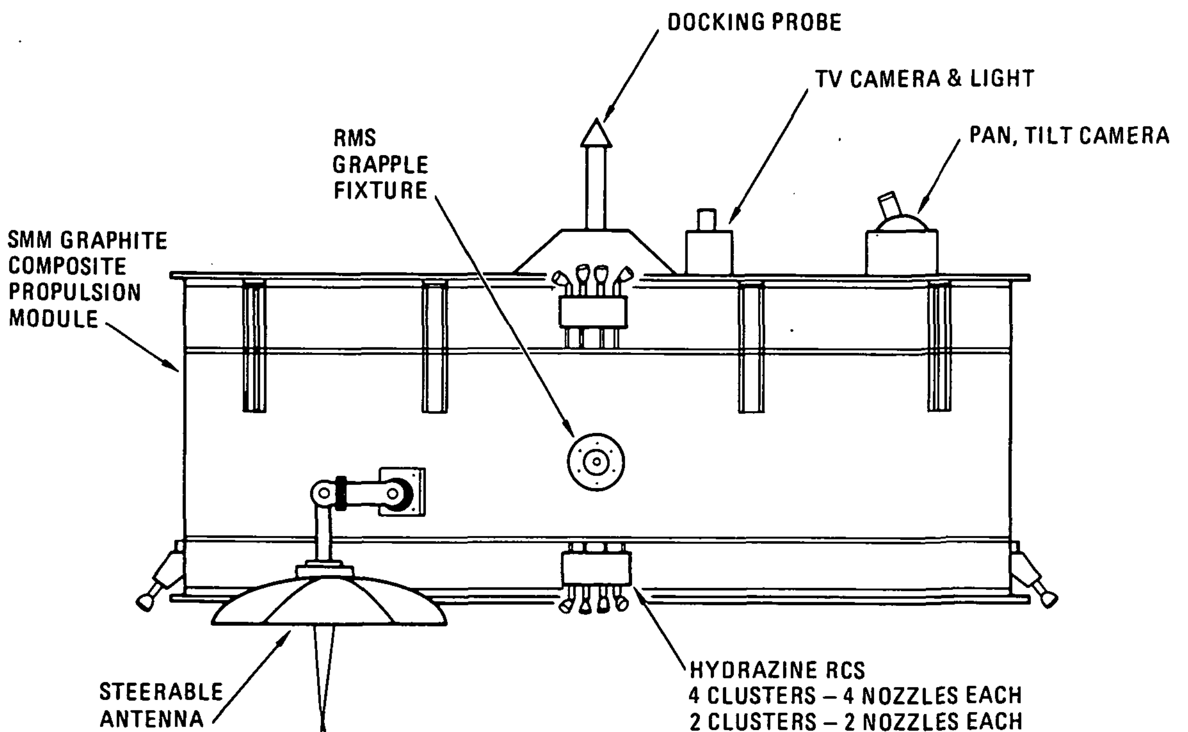

Figure 2-20. Baseline TMS Concept

It carries 5,000 pounds of monopropellant and weighs 7800 pounds. In addition to the propellant tanks and propulsion and reaction control thrusters it includes the following subsystem equipment: a docking kit, docking camera and lights, command control avionics, S-band antennas, range-rate system and antennas, star trackers, pressurization system, inertial reference unit, power system, and thermal control system. A structure is provided to integrate this into a single unit and interface with the Shuttle payload bay as well as the payloads to be maneuvered.

The baseline TMS is compatible with the early Space Station and can provide Space Station services. System requirements for a Space Station based TMS are shown in Table 2-13. They are driven by the station's requirement for assembly, servicing, and maintenance, as well as emplacement, service and retrieval of a wide variety of Space Satellites and other potential space payloads. Command and control, and real time knowledge of the TMS situation by the remote TMS Operator is required.

Key issues are an extension of those which are a function of shuttle compatibility as a result of Space Station basing. Plane change limitations are at issue because the TMS concept is significantly smaller than the OTV with which it is compatible. The remote operator aspect of the TMS makes the development of Robotic Satellite servicing equipment essential.

2.2.2.2 TMS Performance Capability. The Baseline TMS provides the performance capability shown in Table 2-14 for orbits coplanar with the Space Station. The two mass numbers presented for the satellite emplacement operation show the penalty incurred by a requirement for a reaction control system budget.

Table 2-13. Space Based TMS Requirement and Issues

- SYSTEM REQUIREMENTS

  Long Lifetime Systems
  Universal Payload Mating Capability
  Rendezvous and Docking Capability
  Satellite Emplacement, Servicing, Retrieval Capability
  Remote Operator Command and Control Capability
  TMS Orbital Position, Navigation Capability

- KEY ISSUES

  Long-Term Space Exposure
  Space Station Servicing of TMS
  Low Cost (Better Matching to Small Space Jobs)
  Quick Turnaround (Quick Test/Change Components)
  Compatibility with OTV
  Plane Change Limitations
  Robotic Satellite Servicing Equipment

Table 2-14. TMS Performance Capability (No Plane Change)

OPERATION	ALTITUDE (km)	MASS (kg)
Emplacement	550	*7.7-9.5
	1250	*3.6-4.5
**Servicing	550	5.5
	1250	.5
Retrieval	550	8.2
	1250	1.4

*Lower value reflects 5 percent RCS budget.
**Servicing mass is payload carried both ways (Emplacement and retrieval of the payload mass)

As a maneuvering system the TMS can provide small plane change options to lower orbit altitudes or with smaller payload masses.

The TMS based on a space station is not constrained as significantly by the Shuttle payload bay limitations and can have its performance capability increased by modular tankage additions. These would logicaly not be large enought to approach OTV capability, especially since the OTV could be off-loaded for lesser mission requirements.

2.2.2.3 TMS Missions. A list of potential TMS missions is shown in Table 2-15. It indicates the wide variety of services that can be accomplished. The early TMS missions are performed operating from the Shuttle with the baseline TMS. Later missions would operate from the Space Station base. One important set of early missions occurs during the assembly of the space station itself. Early Space Station components need to be maneuvered into position for assembly and these assemblies will be maneuvered and mated into the final space station complex. Shuttle-Station payload transfer will begin with Station components as the payload. Later the payloads transferred to the station will be logistical items such as propellants, life support, etc., and satellites for later emplacement.

Defined missions for TMS with the baseline capability will be limited because of the conceptual size limitations for the vehicle to missions in near coplanar orbits to that of the Space Station. The Space Station 28.5 degree orbit inclination will therefore set the TMS mission orbit inclination. The Space Station program detached payload scenario missions in this orbit inclination are listed with their pertinent characteristics in Subsection 2.1.1 and Table 2-2.

Table 2-15. T.M.S. Missions List -- Civil

- SPACE STATION SERVICES
  - -- Space Structure Component Assembly
  - -- Deployment/Retrieval of Coorbiting Satellites
  - -- Satellite Coorbit Adjustment
  - -- Materials Processing Payload Module Exchange
  - -- Manned Module Local Transport
  - -- Capture of Near Coorbit Debris
  - -- Space Station Component Inspection and Maintenance
- OTV SERVICES
  - -- OTV - Station Payload Transfer
  - -- OTV - Station Manned Module Transfer
  - -- OTV - Near Station Tug
- SHUTTLE SERVICES
  - -- Shuttle - Station Payload Transfer
  - -- Shuttle - Station Manned Module Transfer
  - -- Shuttle - Near Station Tug
  - -- Shuttle - External Servicing
- SATELLITE SERVICES
  - -- Satellite Inspection and Servicing
  - -- Satellite Injection and Retrieval
- DECAYING SATELLITE SERVICE
  - -- Reboost or Controlled Reentry

The TMS has small plane change capability and thus is limited to satellite servicing in near 28.5 degree orbits. The definition of mission types is as follows: For emplacement missions the TMS delivers the satellite from the Space Station to the proper orbit, releases it in the proper orientation, and returns to the station empty.

For the retrieval missions, the TMS travels to the satellite orbit, rendezvous and connects with the satellite (with suitable docking or grappling means) and returns with the satellite to the space station.

For the service mission the TMS carries payload (components/consumables) to the satelite, delivers and/or exchanges the payload and returns with a payload to the station.

Table 2-16 shows space station based TMS mission potential indicating its enhancement of the capabilities of several space systems.

Table 2-16. Space Station Based TMS Mission Potential

SPACE SYSTEM	MISSION DEFINITION	TMS CAPABILITY		
		EMPLACEMENT	SERVICE CAPABILITY	RETRIEVAL
• SHUTTLE	COMPONENT TRANSFER/ASSEMBLY SPACE STATION UNITS TO ASSEMBLY POINT – SOME PAYLOADS/MANNED MODULES			
• OTV	PAYLOAD/MANNED MODULE WITH SPACE STATION			
• SPACE STATION	STRUCTURE ASS'Y, AND FOLLOW-ON MAINTENANCE			
• GEO PLATFORM	OTV PAYLOADS TO ASSEMBLY POINTS, FOLLOW-ON MAINTENANCE			
• SPECIFIC SATELLITES				
. LARGE DEPLOYABLE REFLECTOR	SERVICE		3540 Kg	
FAR U.V. SPECTROSCOPY EXPLORER	EMPLACE, SERVICE, RETRIEVE	√	10450 Kg	√
VERY LONG BASE-LINE INTERFEROMETER	EMPLACE, RETRIEVE	√	10450 Kg	√
SPACE TELESCOPE	SERVICE		5000 Kg	
SHUTTLE IR TELESCOPE FACILITY	SERVICE		10450 Kg	
GAMMA RAY OBSERVATORY	SERVICE, RETRIEVE	√	10450 Kg	√
ADV X-RAY ASTROPHYSICS FACILITY	EMPLACE, SERVICE	√	6820 Kg	√
X-RAY TIMING EXPLORER	EMPLACE, RETRIEVE	√	10450 Kg	√

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2.2.2.4 TMS Options. The baseline TMS is shuttle compatible and shuttle based. As such, it is refurbished on the ground with well understood earth-bound procedures. It can be retrieved by the Shuttle with the rendezvous accomplished by the maneuvering capability of the TMS and can be resupplied in the shuttle so a TMS in good condition can be turned around for more than one service mission on a single shuttle mission. Minor refurbishment might be accomplished at such a turn around by significant repair capability for TMS in the Shuttle, but this is unlikely.

Although the baseline TMS is strongly constrained by the requirement that it be compatible with the Shuttle Orbiter, space station basing of the TMS will remove, or at least mitigate such constraints. For instance, there is the option of resizing a space station based TMS to give increased performance. This could be accomplished by unitary or modular means. A bigger, i.e., longer, not larger in diameter, TMS could be one of the first shuttle payloads for the Space Station complex, or strap-on tank or system modules could be used instead.

A Space Station based TMS should be capable of refurbishment at the station. This will add some requirements, or at least increase the priority of some requirements at the design stage of the space based TMS. Replacement of defective components will need to be easily accomplished. Automated testing of systems will be very important. Also, the systems must be fail operational, with an alternate system path to ensure that the TMS will return to the Station, and not be lost, after system malfunctions.

Some Space Station based TMS options are indicated in Table 2-17. TMS sizing could conceivably range all the way from an off-loaded baseline TMS

Table 2-17. TMS Options -- Space Station Based

- SIZING OF TMS
  - -- Minimum - Low Mass, Local Space Station Servicing
  - -- Intermediate - All Minimum Capability Plus Co-Orbit Satellite Ops.
  - -- Maximum - All Intermediate Plus Orbit Transfer and Plane Change
    -- Near Off Loaded OTV Capability
- PERFORMANCE OF TMS
  - -- Maximum Size - Off Loaded for Lesser Missions
  - -- Intermediate Size - Off Loaded for Minimum, No Maximum Capability
  - -- Minimum Size - Doubled for Intermediate Missions, Tripled for Special Tankage or Maximum Missions
- CONTROL OF TMS
  - -- Surface Based
  - -- Shuttle Based
  - -- Space Station Based
  - -- Autonomous TMS Control

to one that was nearly of the capability of an off-loaded OTV. The maximum size for the TMS probably would be decided by the trade-off in overall efficiency between a growth TMS and an off-loaded OTV. The baseline TMS might be forced to grow significantly if an otherwise suitable TMS mission required more than a few degrees of plane change capability.

The approach to Space Station based TMS would depend on the size of the unitary TMS. As indicated in Table 2-17 a maximum sized TMS could be off-loaded for lesser missions, while a minimum sized TMS would have to be augmented by some means for all but the easier missions. Trade studies will obviously be required to determine which of the approaches would result in more nearly optimum TMS concepts.

Sizing of orbital transfer vehicles for optimum operational capability is a very complex study and it may be that size limits for the TMS could be effectively set by an arbitrary decision.

There are obvious Command Control options for the TMS. For primary consideration, all the options can be applicable to TMS control. The baseline TMS is controlled from an earth base. Considering the fact that an orbiting TMS will move out of contact with the ground controller, this obviously requires space satellite relay systems as well as the ground base command and control complex. For a space station based TMS, control from the station is an obvious first option and would be especially advantageous for a TMS engaged in Space Station servicing activities. Shuttle based control is an option that could provide significant advantages during early space station assembly efforts. For some missions, especially ones in which crew capsules or other manned systems are TMS payloads, backup control from the payload might be a good option and finally autonomous control by the TMS itself is an option that might become a requirement especially in an unfriendly environment where TMS communication could be disrupted.

There are options also in the kinds of command and control equipment that could be utilized by the TMS. There are several systems that could be used in all the technology areas that impact on the command and control of the TMS. Table 2-18 indicates some of the systems options available for: data acquisition, electrical power supply, rendezvous and docking, communication paths, inertial reference, range and rate sensors, antennas and attitude control systems.

Other technology areas have options that should be considered for the Space Station based TMS. This is especially true since some of the impact of Shuttle constraints on the baseline TMS is relieved or otherwise modified. Table 2-19 lists some of these technology areas and the option approaches available. Trade studies in all these areas will determine the final choice.

Table 2-18. TMS Options -- Command and Control

TECHNOLOGY AREA	OPTIONAL APPROACHES
• Data	STACC - DACS - FMDM - Video
• Electrical Power	Solar Arrays - Primary Batteries - Fuel Cells
• Rendezvous, Docking	Orbiter Ku Radar - Radar Altimeter Conversion - Aircraft/Missile Systems Conversion - Millimetr Wave - Laser - Optical Systems
• Communication Paths	Ground/TMS via TDRSS - Orbiter/TMS Direct - Orbiter/TMS via TDRSS - Space Station/TMS Direct
• Inertial Reference Systems	DRIRU II - SIRCA - ATVCA
• Range/Range Rate Sensors	ED - Laser Radar - Gated TV - Video Photogrammetry - Pulsed Radar Altimeter - DME - Orbiter Radar (Pulse) Mining Radar (FM-CW) - Hybrid Pulse Doppler and PN - CW - Random Signal Radar
• Antenna	Omni W/Steerable Horn - Autonomous Omni Antenna System
• Attitude Control System	MMS - MACS Module - Global Positioning System - Sun Sensor - Star Tracker - Horizon Scanner - Television

2.2.2.5 TMS Trades. Table 2-20 lists some of the TMS trades that should be studied and resolved for the Space Station based concept. Sizing of the TMS will determine whether a common TMS design or several different TMS designs make the best system and whether there must be several TMSs at the station or the station can be usefully serviced with only a few.

The desire for maximum performance with any system must be tempered with the knowledge of the effects of modifications for increasing the performance. Several performance trades are indicated.

Command and control has been discussed and certainly there are trades to be understood in this technology also.

There are ultimately many more trades, than listed here, that will be made before the TMS is based on a Space Station. Some will be accomplished very easily, almost intuitively, others will require study in significant depth to achieve understanding of the overall ramifications for the Space Station system.

Table 2-19. TMS Configuration Options and Trade-Offs

TECHNOLOGY AREA	OPTION APPROACHES
• Propellant	• Storable Monopropellants Delivered - Cryogenics Delivered. • Cryogenics Scavenged - N_2O_4/MMH Delivered
• Thrusters (Main)	Gimballed Single - Throttled Multiple
• Electrical Power	Primary Battery - Solar Array - Fuel Cells
-- Primary Battery	AgZn - Li So Cl_2
-- Solar Array	• NiCd Battery - NiCo and AgZn Batteries • Array on TMS Surface - Array Deployed
-- Fuel Cells	• Orbiter Type - Reduced Version
• Structure	• Unitary Resizing - Modular Growth. Cantilever - Noncantilever Payload Capability
• Thermal Control System	• Individual Thermal • Enclosures - Cocoon - Active - Passive

Table 2-20. TMS Trades -- Space Station Based

- SIZING OF TMS
  - -- Several TMS Designs vs Common TMS Design
  - -- Many Different TMS vs Few TMS at Station
- PERFORMANCE OF TMS
  - -- Effects of Large, Off Loaded, Tank Systems on Mission Capabilities
  - -- Effects of Doubling or Tripling vs Special Tankage
  - -- Max TMS Capability vs Off Loaded OTV
- CONTROL OF TMS
  - -- Surface Based - Multiple Bases vs Orbiting Relays vs Partial Orbit Control
  - -- Space Based - Coorbit vs Longer Ranging Requirements
  - -- Autonomous - Partial vs Complete vs Preprogrammed vs Man in Place

2.2.2.6 TMS Architectural & Evolutionary Concepts. The development of the Early Space Station based TMS will follow an orderly path starting with the baseline TMS designed to be compatible with and enhance the capability of the Shuttle. The early TMS is capable of helping to deliver and assemble the early space station components. It is also able to emplace, service, and retrieve satellities in near co-planar orbits to its base (Shuttle or early Space Station).

Further TMS concept evolution will enable basing on later Space Stations (perhaps in polar orbit) and therefore enable servicing of satellites in higher inclination orbits. The TMS will be more independent of the Shuttle and more capable of quick turnaround and maintenance at the Space Station base.

Table 2-21 indicates some of the arichitectural and evolutionary concepts that will take place in the development of the TMS for basing on earth orbit space stations.

Table 2-21. TMS Architectural and Evolutionary Concepts

- INITIAL TMS CONCEPT
  - Compatible With Shuttle
  - Sized to Maximize Shuttle Payload Capacity in Low Earth Orbit
  - Capable of Emplacing, Servicing, & Retrieving Satellites to 600 km
  - Storable Monopropellants
  - Ground Based Command & Control of TMS
  - Payloads Sized to Fit Shuttle, Cantilever Support Capability
  - Space Station Assembly Capability
- EARLY SPACE STATION BASED TMS CONCEPT
  - Modular for Increased Performance
  - Modules Transportable by Shuttle
  - Command & Control from Space Station or Ground
  - Storable Propellant or Scavenged Cryogenics
  - Complementary to OTV
  - Capable of Emplacing, Servicing, & Retrieving Satellites to 600 km
  - Payload Dimensions (Assembled) Not constrained by Shuttle
  - Space Station Assembly & Maintenance Capability
- LATER SPACE STATION BASED TMS CONCEPT
  - Modular for Increased Performance
  - Maintainable on Space Station
  - Command & Control on Space Station
  - Autonomous Control Possible (Manned)
  - Capable of Emplacing, Servicing, and Retrieving Satellites to Higher Orbits and Inclinations
  - Capable of Noncooperating Satellite Recovery
  - Rapid Mission Turnaround
  - Decaying Satellite Reboost or Accurate Reentry Capability

To achieve the development of the TMS will require advances in a large number of technologies. Table 2-22 indicates some of these technologies.

The basic driver for all TMS technology development is to improve the mass ratio of the system and its equipment and thus its space operational performance. Another driver is a quest for increased reliability of components considering the remoteness of the system in the event of a component failure and the costs associated with all space missions.

The most important subsystem technologies for the TMS apply to the development of remote assembly, inspection, and repair capability, better command and control systems, improved space propulsion and attitude control, and improved thermal control in space.

To increase the utility of the TMS a universal mating capability for all spaceborne systems is a worthwhile development.

Table 2-22. Required TMS Technology

- Technology Development in All Areas to Improve Overall T.M.S. Mass Ratios & Enhance the Capabilities of the Total Space System
- Improved Material Properties for Space Structural Applications Along With Better Understanding of Space Structural Requirements
- Development of Remote Assembly, Inspection, & Repair Capability for Space Applications & Utilization
- Selection & Development of Improved Command & Control Subsystems
  - -- Electrical Power
  - -- Remote Rendezvous & Docking Systems
  - -- Inertial Reference Systems
  - -- Optimized Communication Paths
  - -- Improved Data Collection & Real Time Viewing Capability
- Improved Propulsion & Reaction Control System
  - -- Propellants - Selection & Handling
  - -- Motors - Throttable and Gimballed
- Selection & Development of Improved Thermal Control Systems
- Long Space Environment Life for all Systems
- Universal Mating Capability for all Space System

2.2.2.7 TMS Operations TMS operations are similar to OTV operations, especially when considering an advanced space-based TMS concept with modular construction. However, TMS operations in this study are centered around a Shuttle configured baseline TMS that operates from the Space Station. Otherwise, TMS operations would be almost indistinguishable from that already described for the OTV.

The top-level TMS operations are presented in Figure 2-21. The major differences in TMS operations compared to OTV occur in the delivery and maintenance options. The TMS is also returning payloads to the Station, which is a variation from OTV scenarios.

The TMS is transported to the Space Station by Shuttle. The TMS, because of its size, is delivered as a complete assembly. The TMS can be fueled or empty. Three options are considered for TMS transfer from the Shuttle to the Station:

a. Transfer the TMS from the Shuttle to the Space Station maintenance dock with an RMS.

b. Separate the TMS from the Shuttle normally under its own power, rendezvous and dock with the Space Station maintenance dock.

c. Separate the TMS from the Shuttle with a payload attached, perform a mission operation, return to the Station to rendezvous and dock with the maintenance dock.

TMS retrieval offers the same options as those outlined for the OTV. The TMS can dock directly with a docking arm or rendezvous within the range of an RMS which grasps the vehicle and places it in the maintenance dock.

A TMS returning to the Station with a payload provides some variation in retrieval methods. The TMS approaches the Station within reach of a payload RMS, which grasps the payload. The TMS then separates from the payload and docks, as described in the above options. Another method involves a two RMS capture. The TMS approaches the Station as before and the payload is grasped by one RMS, a second RMS grasps the TMS. The TMS releases from the payload and allows the payload RMS to transfer the payload to a maintenance pedestal. The second RMS then places the TMS in the maintenance dock.

The TMS Level I on-vehicle maintenance functional flow is presented in Figure 2-22. The variations from OTV maintenance operations is minor, since it only involves charging the batteries. Battery conditioning is initiated as soon as the TMS and Station interfaces are verified and continues in parallel with the other operations.

The TMS corrective maintenance functional flow varies appreciably from the OTV operations, as depicted in Figure 2-23. The TMS is compact enough to be returned to earth intact on the Shuttle for any maintenance operations, if the condition of the vehicle is safe for transport on the Shuttle. The compactness of the baseline TMS also works against maintainability in space, because it is difficult to remove and replace damaged or failed components.

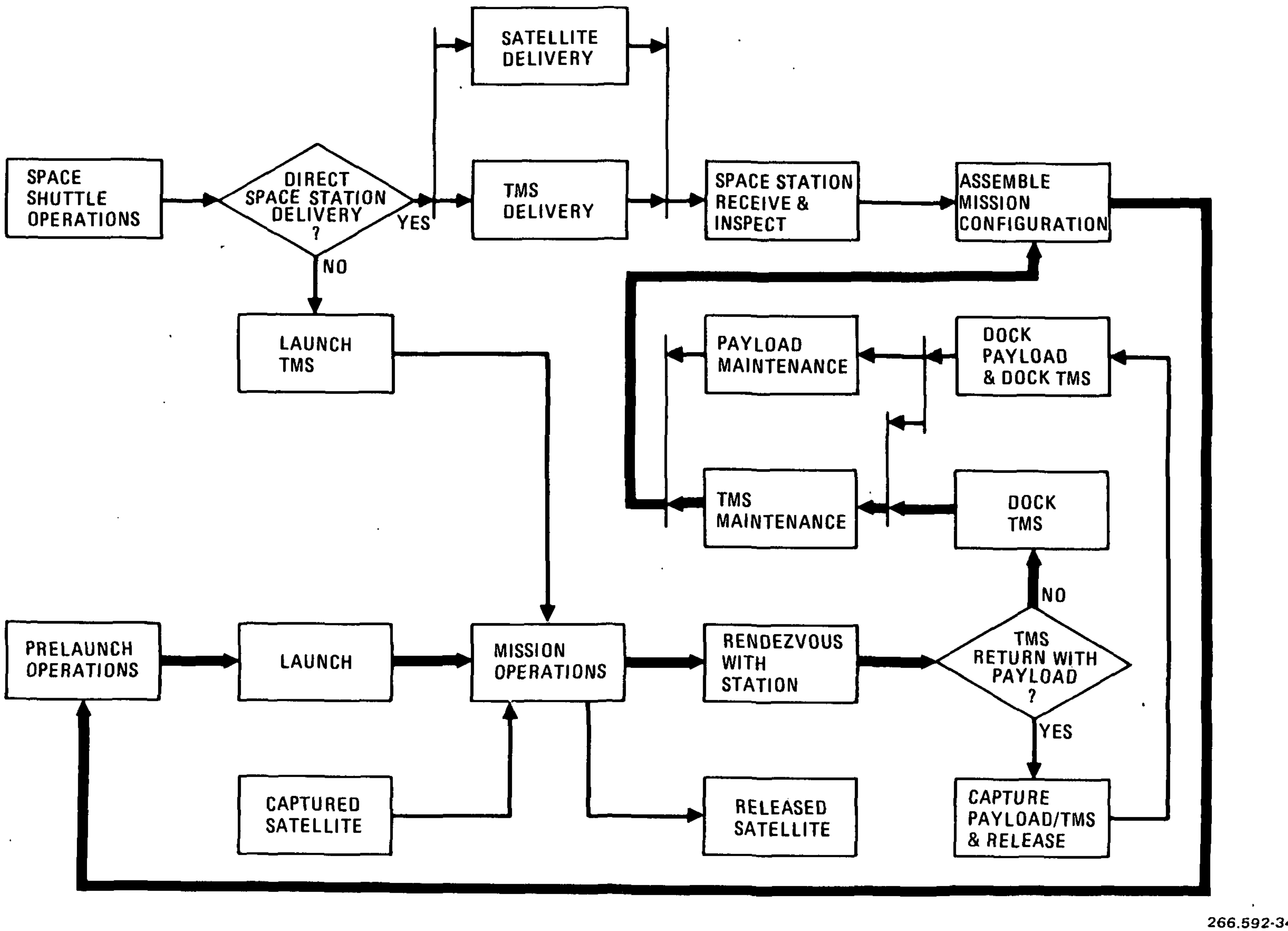

Figure 2-21. Top Level TMS Operations

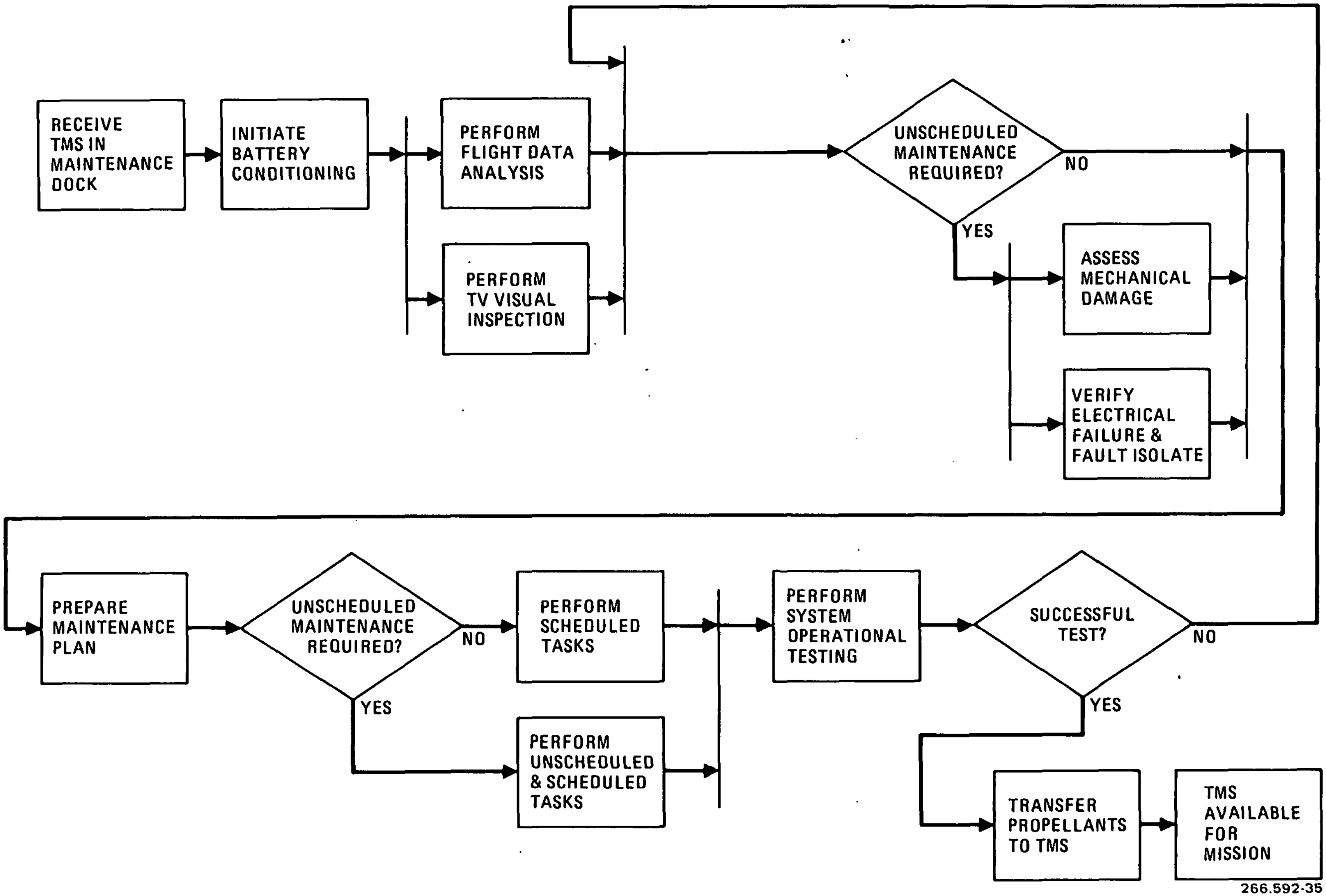

Figure 2-22. TMS Level I Maintenance Functional Flow

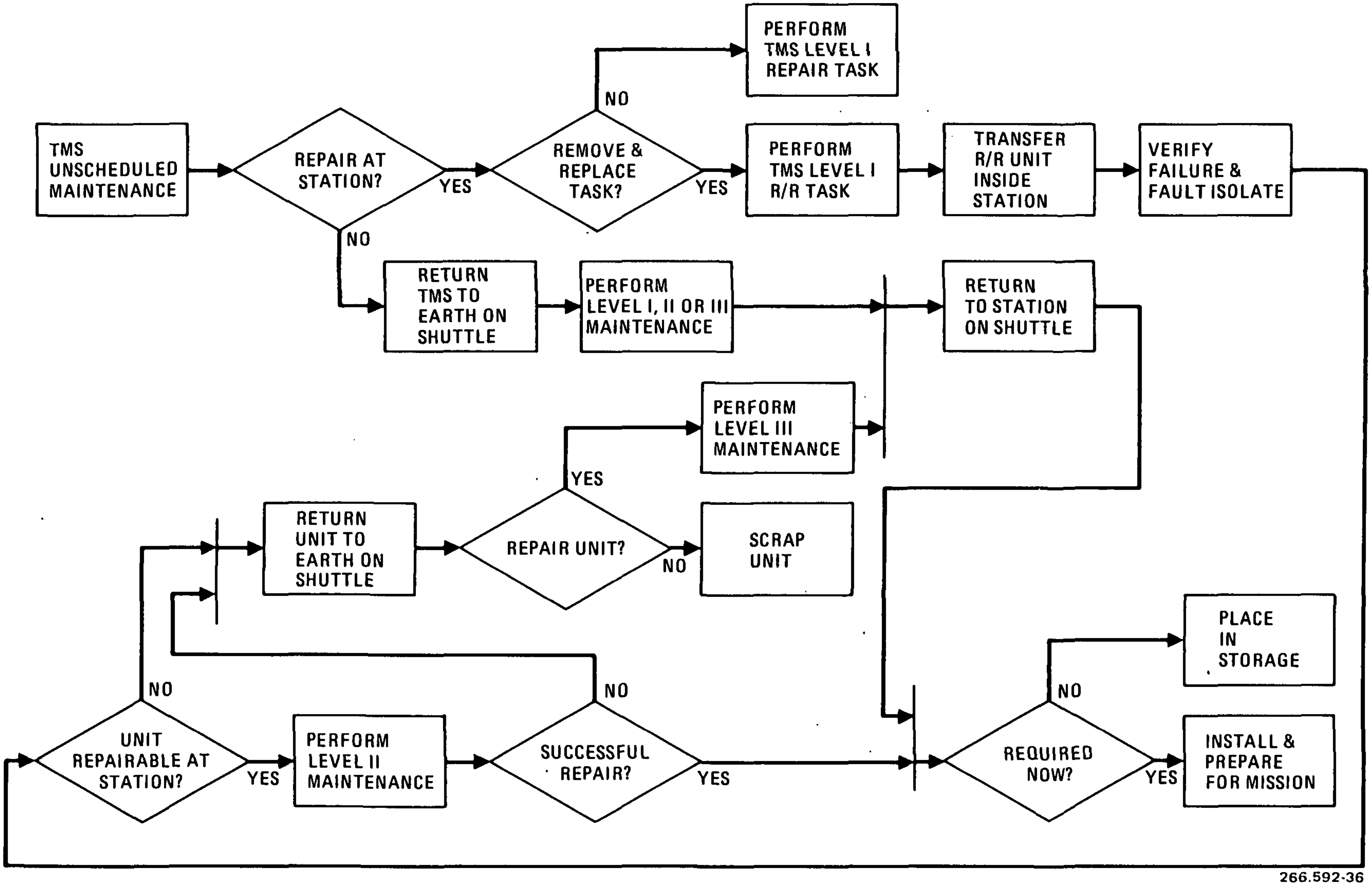

Figure 2-23. Shuttle/TMS Corrective Maintenance Functional Flow

It is most likely that any repair activity on this vehicle would involve EVA operations.

An example of removal and replace operations is shown in Figure 2-24 along with a satellite delivery (Figure 2-25), in-situ satellite servicing (Figure 2-26) and satellite servicing at the Space Station operations (Figure 2-27).

Payload integration with the TMS is described in Subsection 2.2.4.

2.2.3 SATELLITE SERVICING OPERATIONS. The Space Station concept provides for convenient staging of satellite and propulsive vehicle resources in support of satellite orbit delivery and on-orbit servicing operations. The Station also accommodates on-station maintenance of satellites retrieved from on-orbit duty. These satellite and vehicle activities are presented in Figure 2-28, the top level diagram for Space Station satellite servicing operations. The staging scenario involving the Shuttle delivery of satellites to the Station, where they are assembled, checked out, integrated with an orbital transfer vehicle, and subsequently placed in orbit or trajectory, is the topic of Subsection 2.2.4, Payload Processing and Integration Operations. The space based OTV and TMS operations are presented in Subsection 2.2.1.4 and 2.2.1.7, respectively.

2.2.3.1 Satellite On-Station Maintenance Operations. Maintenance operations are presented here as the top level function of preparing or restoring a satellite to achieve a desired operational capability. Some maintenance tasks in this operation include handling, assembling, servicing, repair, inspection, and checkout. The servicing aspect is fully apparent during cleaning, decontamination, replenishment of propellants, and other consumables. Satellites will also be brought to the Station for reconfiguration, repair and a variety of subtasks associated with these major processes. Figure 2-29 provides the main activities involved in Satellite on-station maintenance operations. A more detailed rendition of the maintenance operations is offered in Figure 2-30, along with a method of satellite and vehicle retrieval. The diagrams are general representations of maintenance operations, which were generated for the purpose of establishing Space Station satellite maintenance accommodations.

A typical satellite retrieval and maintenance operation is conducted in the following manner.

The satellite and propulsive vehicles approach the Station within range of the RMS, which grasps the satellite and allows the vehicle to release. The vehicle backs off to a safe distance and awaits its turn for docking, while the satellite is secured to the Space Station. First, the satellite mating interface is inspected, then it is positioned on a maintenance pedestal and the interface latched. The RMS is released for vehicle capture operations. The satellite will be housed in a shelter; therefore, appendages which would cause an interference with the structure are removed and installed in holding fixtures. EVA operations may be required to perform this task. The shelter is extended to cover the satellite. Visual inspection is performed to identify and assess satellite anomalies.

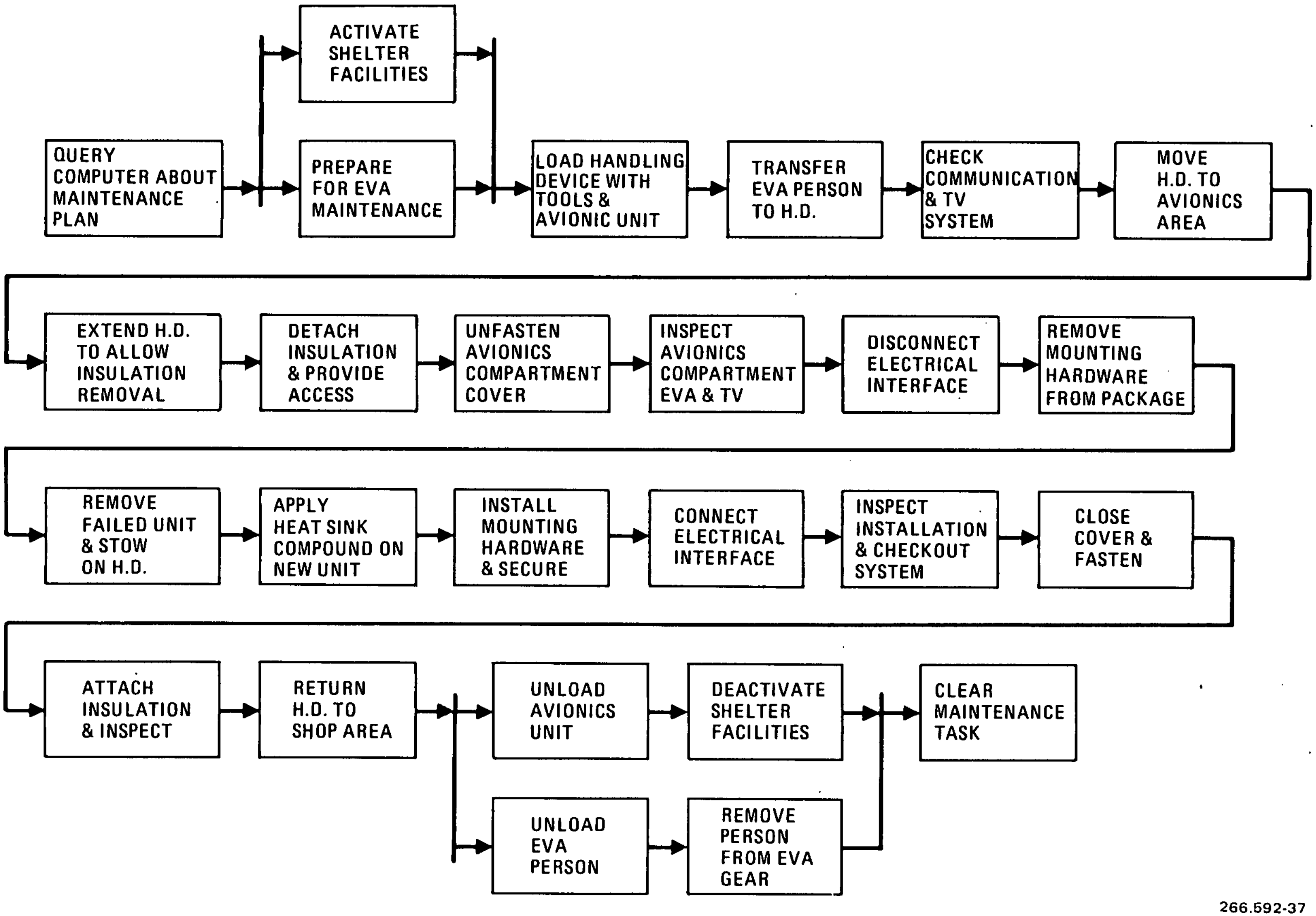

Figure 2-24. TMS Level I Unscheduled Maintenace - R/R Avionic Unit (Shuttle Configuration)

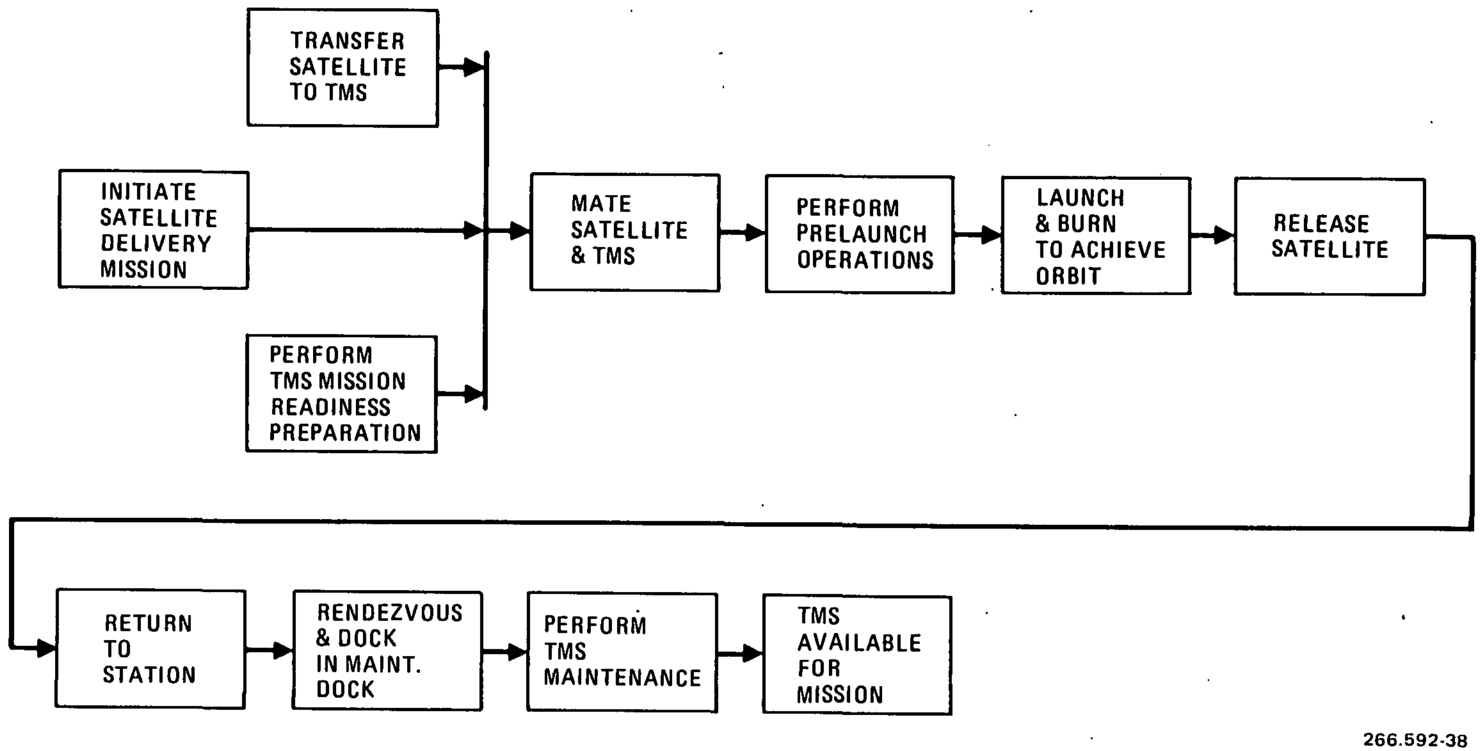

Figure 2-25. TMS Operational Mission - Satellite Delivery

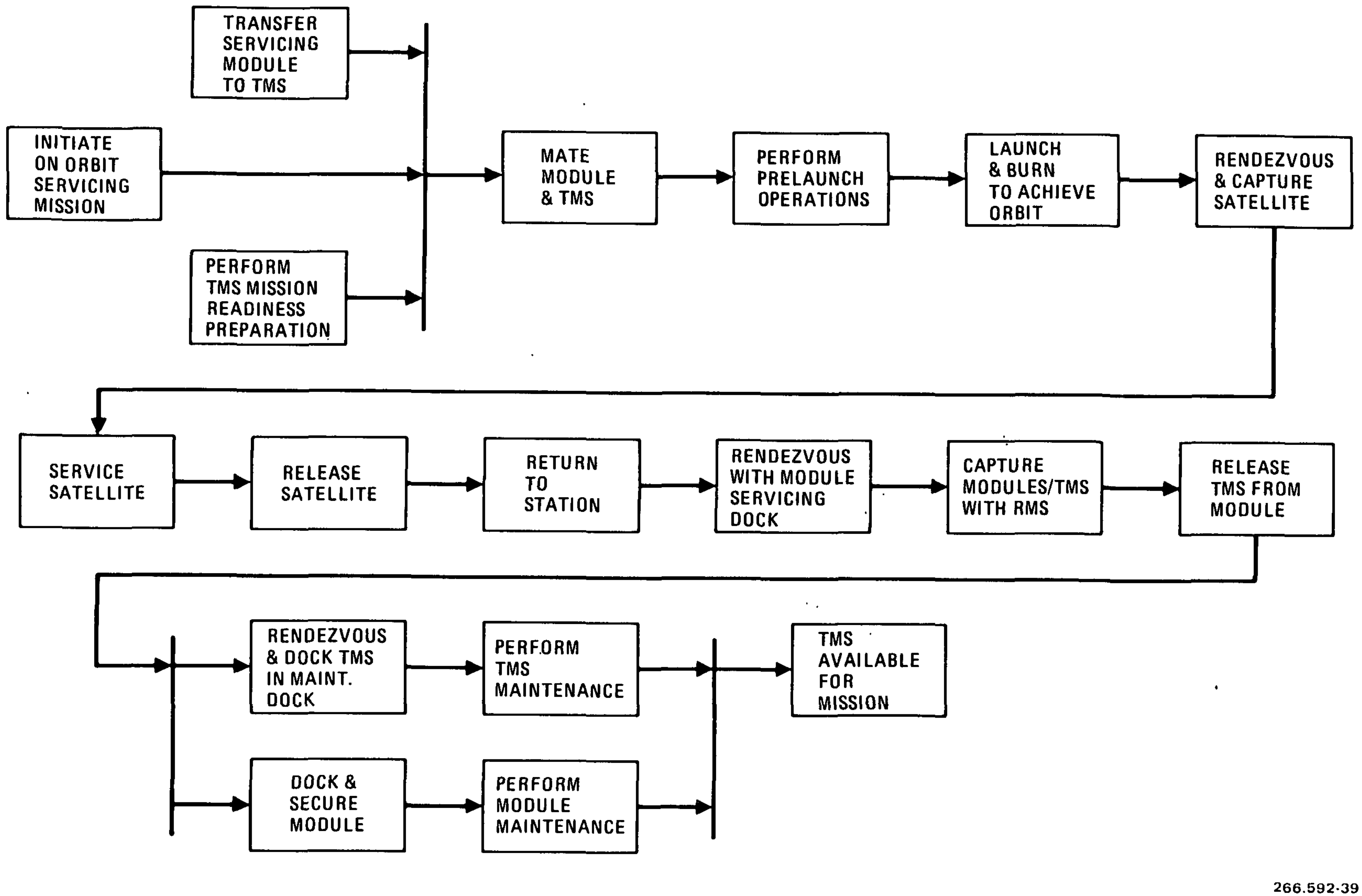

Figure 2-26. TMS Operational Mission - On-Orbit Satellite Servicing

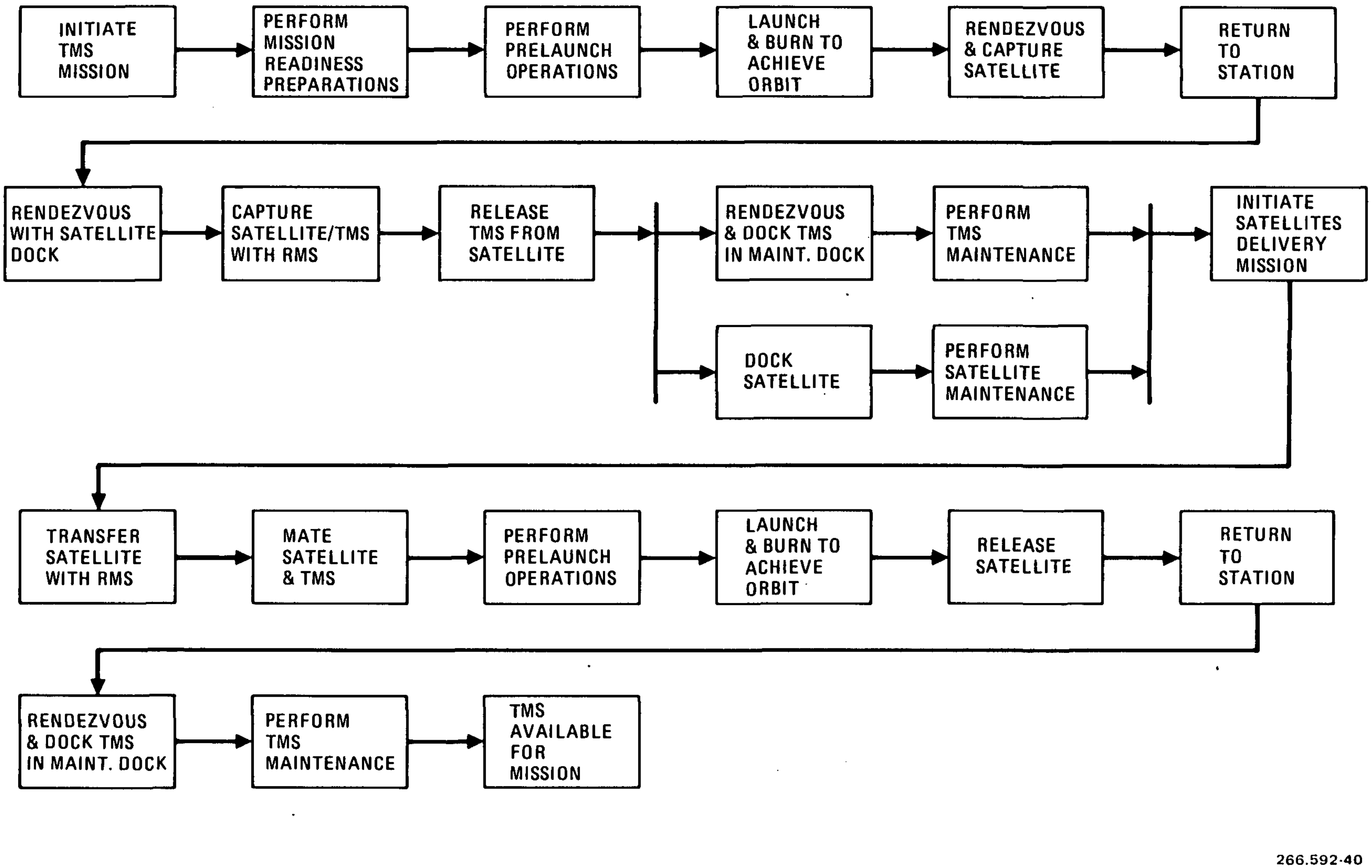

Figure 2-27. TMS Operational Mission Satellite Services at Station

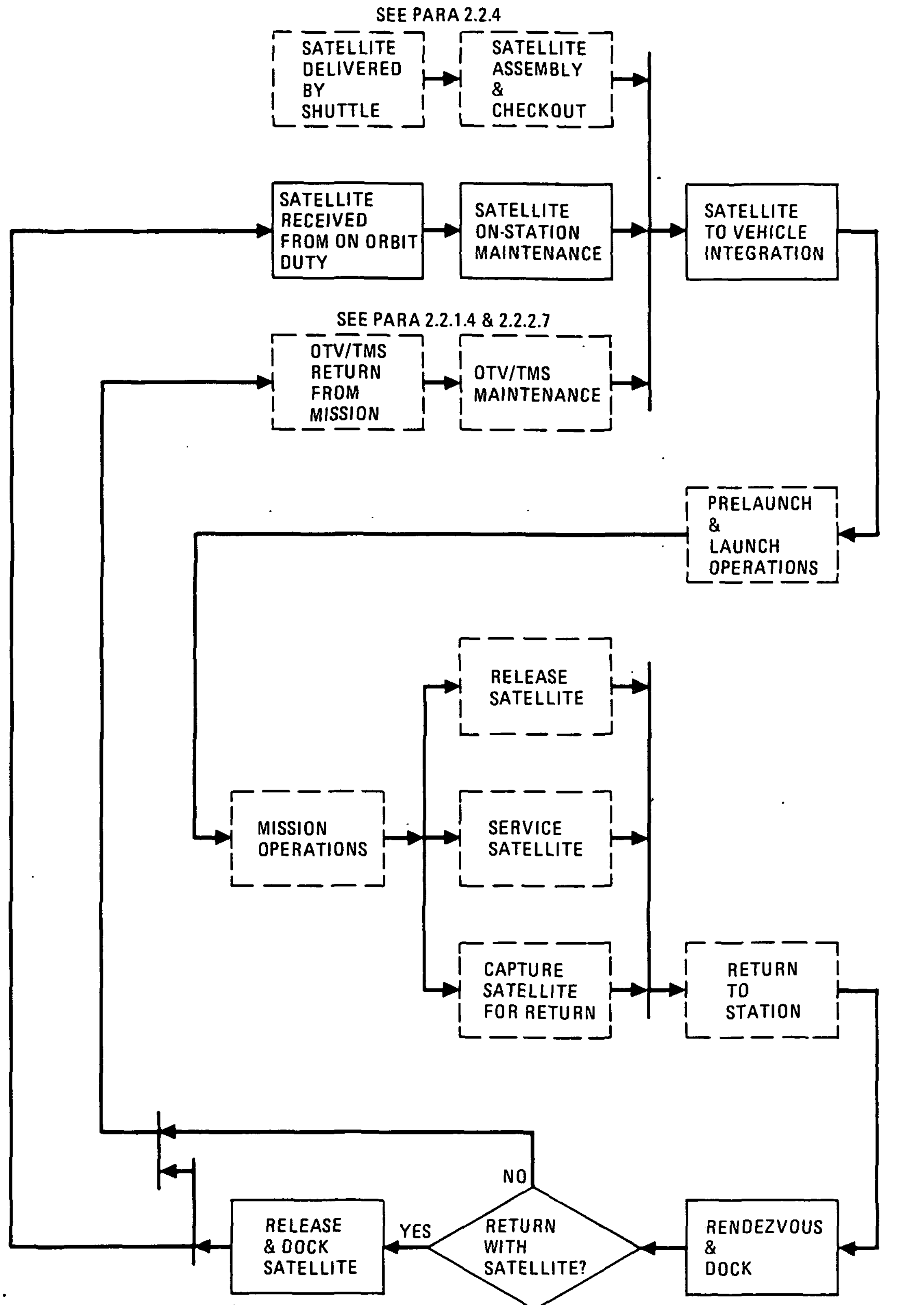

Figure 2-28. Satellite Servicing Operations

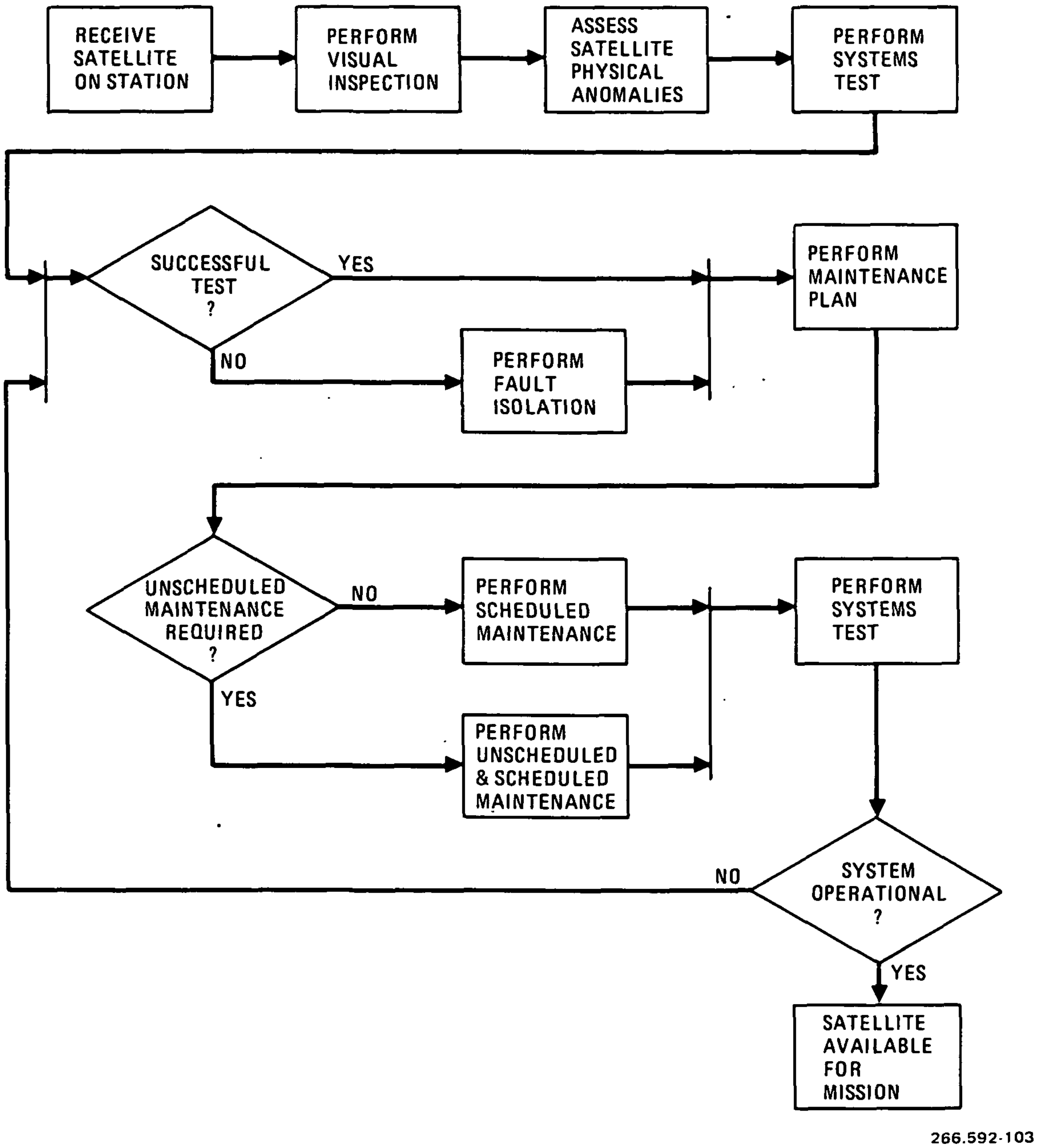

Figure 2-29. Satellite On-Station Maintenance Operations

Figure 2-30. Satellite Retrieval and Maintenance Operations

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If the satellite was adequately functional, while on-orbit, it is now tested to evaluate its condition. If the satellite is not functional, an EVA operation is initiated to troubleshoot, isolate the faults, and repair as necessary to bring this system on line for a systems test. The faults identified as a result of systems testing are entered into a maintenance plan. Satellite components and consumables are readied and further preparations for satellite maintenance are conducted. The remaining scheduled and unscheduled maintenance tasks are then accomplished.

A data link from satellite to relay station to satellite ground station is established to provide for a more complete operational testing of the satellite.

Once the basic satellite system is determined operational, the shelter is retracted and the appendages are installed. The satellite now receives a final operational test before deployment.

The satellite is grasped by the RMS and it is released from the maintenance pedestal. The satellite is positioned and locked on the propulsive vehicle. A satellite to vehicle integration test is performed and this total system is readied for launch operations.

2.2.3.2 Facilities and Support Equipment Requirements. The basic facilities and equipment to support satellite maintenance operations are listed as follows:

a. RMS - including TV, lights, and effector/tool adapter

b. Tools Storage Fixture

c. Shelter - with lights, communication, and TV system

d. Maintenance Pedestal - capable of rotating, with appropriate interfaces

e. Maintenance Module/Control Station - with computer system, communications, data link (hard line and RF), control panels, TV monitors, view port

f. Satellite Component Storage

g. Satellite Propellant and Consumables Storage

2.2.4 PAYLOAD PROCESSING AND INTEGRATION OPERATIONS. Payloads consist of satellites or other spacecraft which are brought to the Space Station for assembly or servicing, where they receive checkout and integration with a carrier vehicle for subsequent transport to their designated orbit or trajectory. The payloads arrive at the Space Station by Shuttle, on initial delivery missions, or may be brought to the Station from on-orbit duty to be serviced. A typical payload and integration operation is presented in Figure 2-31 and a more detailed diagram is contained in Figure 2-32. These diagrams progress through the payload operations from initial delivery by Shuttle to prelaunch operations.

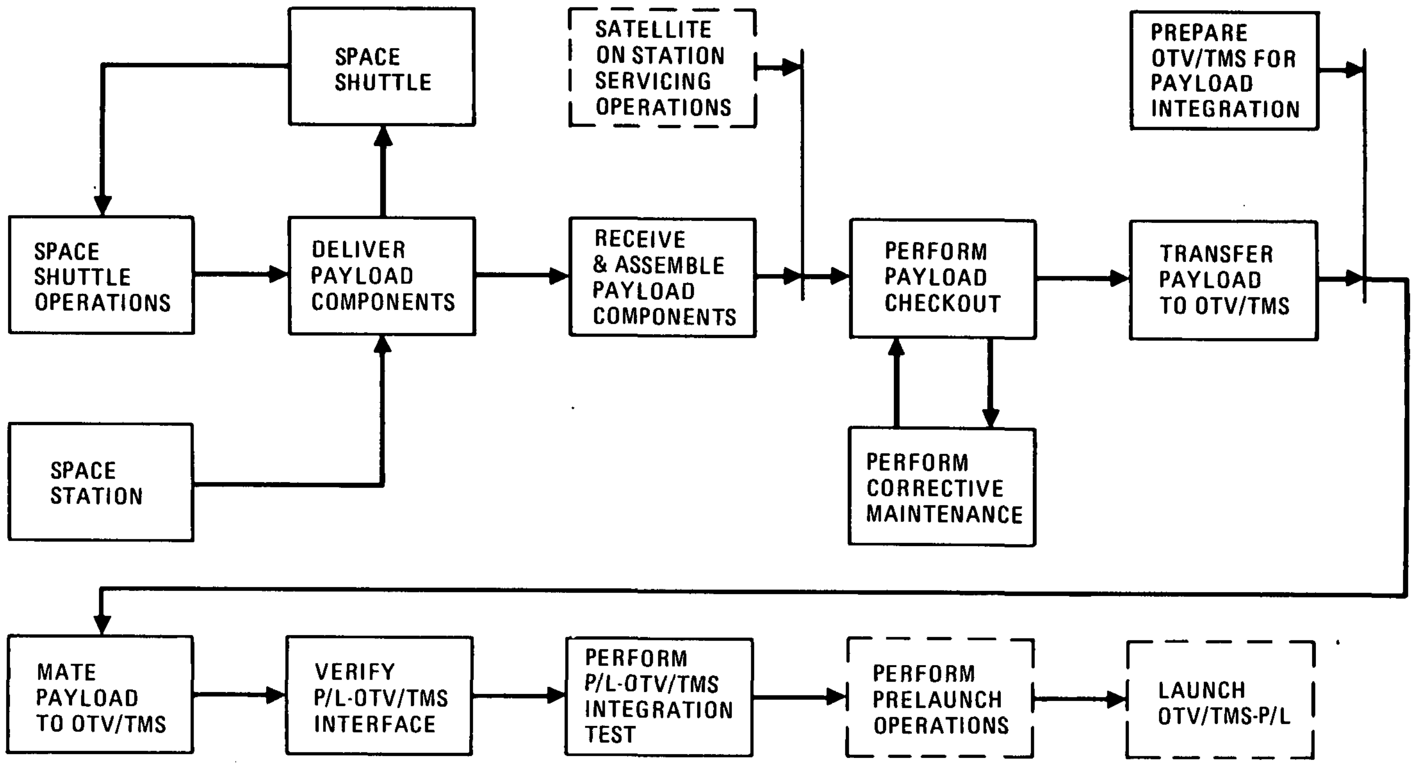

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Figure 2-31. Payload Delivery, Processing and Integration Operations

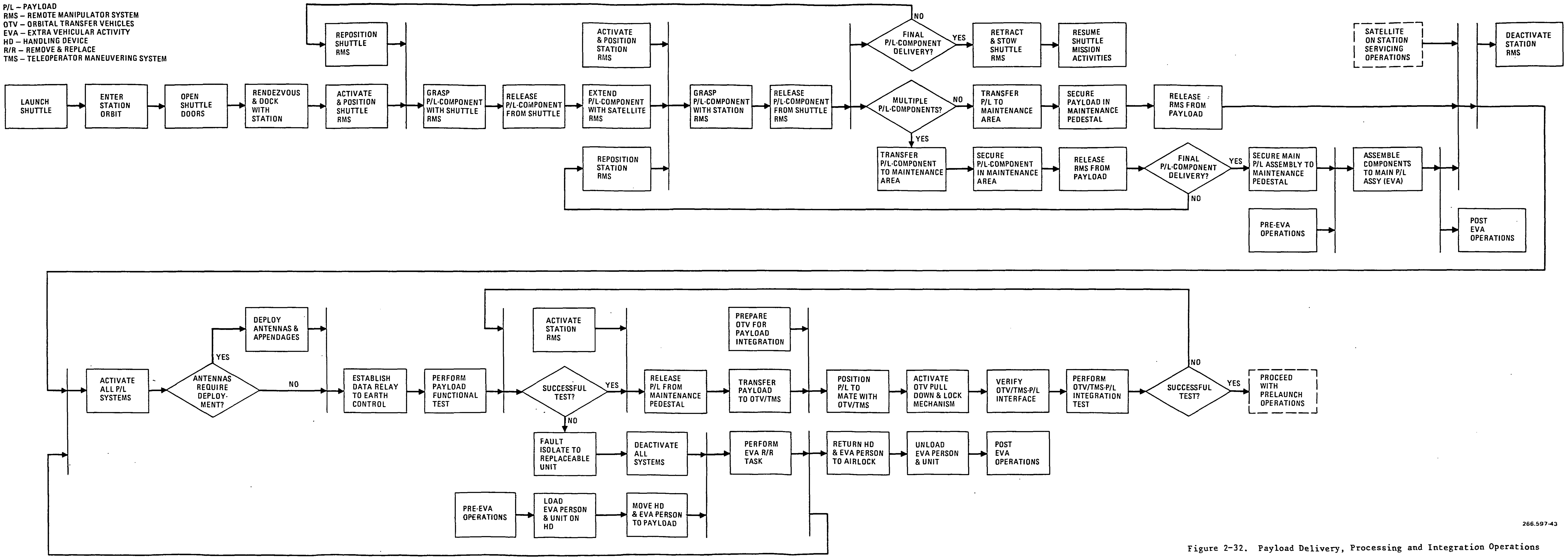

Figure 2-32. Payload Delivery, Processing and Integration Operations

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The payloads are transported to the Station by Shuttle as single units or as multiple components to be assembled. The Shuttle rendezvous and docks with the Space Station and uses its RMS to extend and transfer the payload to the Station RMS. The Station RMS then transfers the payload to a maintenance pedestal. If there are multiple payload components the process is repeated, placing the main payload assembly in the maintenance pedestal and other components nearby in designated holding fixtures. The Shuttle RMS is released, retracted, and stowed as the Shuttle is freed to resume other mission activities. The multiple payload components are assembled utilizing robotics or manipulators, with EVA operations reserved for conditions where uniqueness and complexity of the payload warrant EVA assistance in accomplishing this task.

A payload brought to the Station from on-orbit duty that has received required servicing would enter the operations at this point. Whether brought in by its own propulsion, TMS, or OTV, the payload is placed on the maintenance pedestal for service by the station RMS. The OTV and/or TMS is left in its docking port. Spacecraft internal propulsion is safed before it is brought to the maintenance pedestal.

All payload systems are activated; antennas and appendages are deployed, extended, or attached. The appropriate data links are established to provide the necessary earth station control for operational testing of the payload. If the payload operational test is not successful, the problem is isolated to a replaceable unit. The failed unit is removed and replaced. When the payload achieves satisfactory operational status, it is lifted from the maintenance pedestal with an RMS and transported to a carrier vehicle, either an OTV or a TMS. The payload is positioned and mated with the vehicle and locked. The payload to vehicle interfaces are verified and integration tests are conducted.

Payload integration is now complete and the operation proceeds with prelaunch activities.

2.2.5 SPACE SYSTEMS ASSEMBLY AND CONSTRUCTION OPERATIONS. Considerable effort was expended by General Dynamics Convair in defining the Space Construction Automated Fabrication Experiment (SCAFE), under NASA/JSC contract NAS9-15310 (reference 1). The results of this study produced a viable space platform structure and fabrication equipment for experimental evaluation of an automated fabrication and assembly of large structures in space. The selected platform concept (Figure 2-33) provides an ideal candidate for a construction project to be conducted on a Space Station. The Construction Systems Assembly (CSA) is self contained and transportable to the station on one shuttle flight.

The selected completed platform consists of four triangular beams, each 200 meters long, held together by nine crossbeams which measure approximately 11 meters in length. The size of the structure is expandable to any dimension, dependent on the quantity of beam building fabrication material.

The actual fabrication of the structure is an automatic process, thereby minimizing the amount of EVA involvement. EVA assistance is required for securing the CSA to the station, inspection and experiment equipment installation.

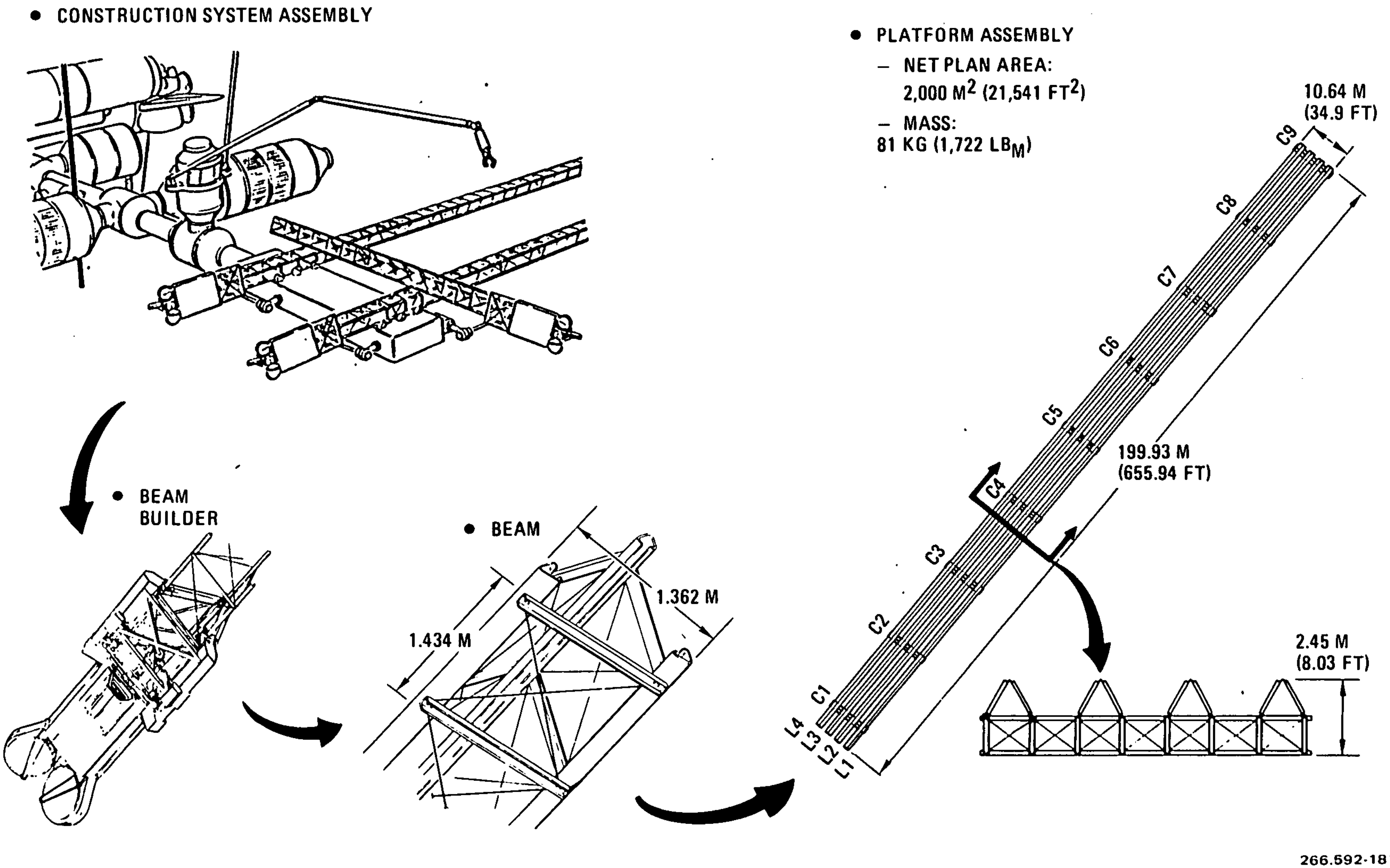

Figure 2-33. Baseline Construction System

2.2.5.1 Mission Operations. Space structure construction operations are presented in Figure 2-34 and a more detailed functional flow is provided in Figure 2-35.

The shuttle vehicle transporting the construction system assembly to the station, rendezvous and docks with the station. The shuttle RMS grasps, extends and transfers the CSA to the station RMS. The station RMS then transfers and positions the CSA on station. The RMS is locked in place and deactivated as a safety measure, to allow EVA operations. EVA personnel secure the CSA to the station and withdraw to a safe location. The RMS is activated, released from the CSA, retracted and stowed. The CSA auto erect program is activated and the system extends to a full deployment attitude. EVA personnel move in to inspect the beam builder equipment to verify proper configuration prior to initiation of automatic beam fabrication. The equipment receives an automatic checkout and EVA personnel conduct post EVA operations. The fabrication program is initiated and the first 200 meter long beam is produced. A dynamic response test is conducted on this first beam to determine its characteristics and the information is transmitted to earth control for evaluation. The remaining three beams are fabricated and all beams are repositioned on the beam builder to accommodate crossbeam attachment. Each of the nine crossbeams are fabricated and attached to the platform. The completed platform structure is now translated on the CSA to prepare for experiment equipment installation. EVA personnel provide a visual inspection of the structure during installation and test of experiment instrumentation and subsystems. EVA personnel return to the airlock for post EVA operations. The dynamic response and thermal deflection experiments are checked for proper operation, then the experiments are performed.

The space platform structure is now prepared for free flight operations. The station RMS is activated and commanded to grasp the platform. The RMS extends the platform after release from the CSA. The TMS is activated, rendezvous and docks with the platform and the RMS releases the mated pair. The platform is maneuvered to its free flyer position and the TMS releases for return to station. Characteristics of the free flyer are observed, monitored, and evaluated. The TMS is called to action for retrieval service and performs a rendezvous and docking operation with the free flyer platform. The platform is maneuvered to the station, where it is captured with the station RMS. The TMS releases control of the platform. The platform is positioned and secured in the CSA as the RMS is released, retracted and stowed.

Once again, the dynamic response and thermal deflection tests are resumed and then terminated prior to the unscheduled maintenance demonstration. EVA personnel demonstrate platform and CSA repairs, then more testing of the structure is conducted.

At the end of the experiment, the RMS transfers the platform to the TMS for placement in a decay orbit trajectory. The shuttle returns to the station and transports the CSA to earth.

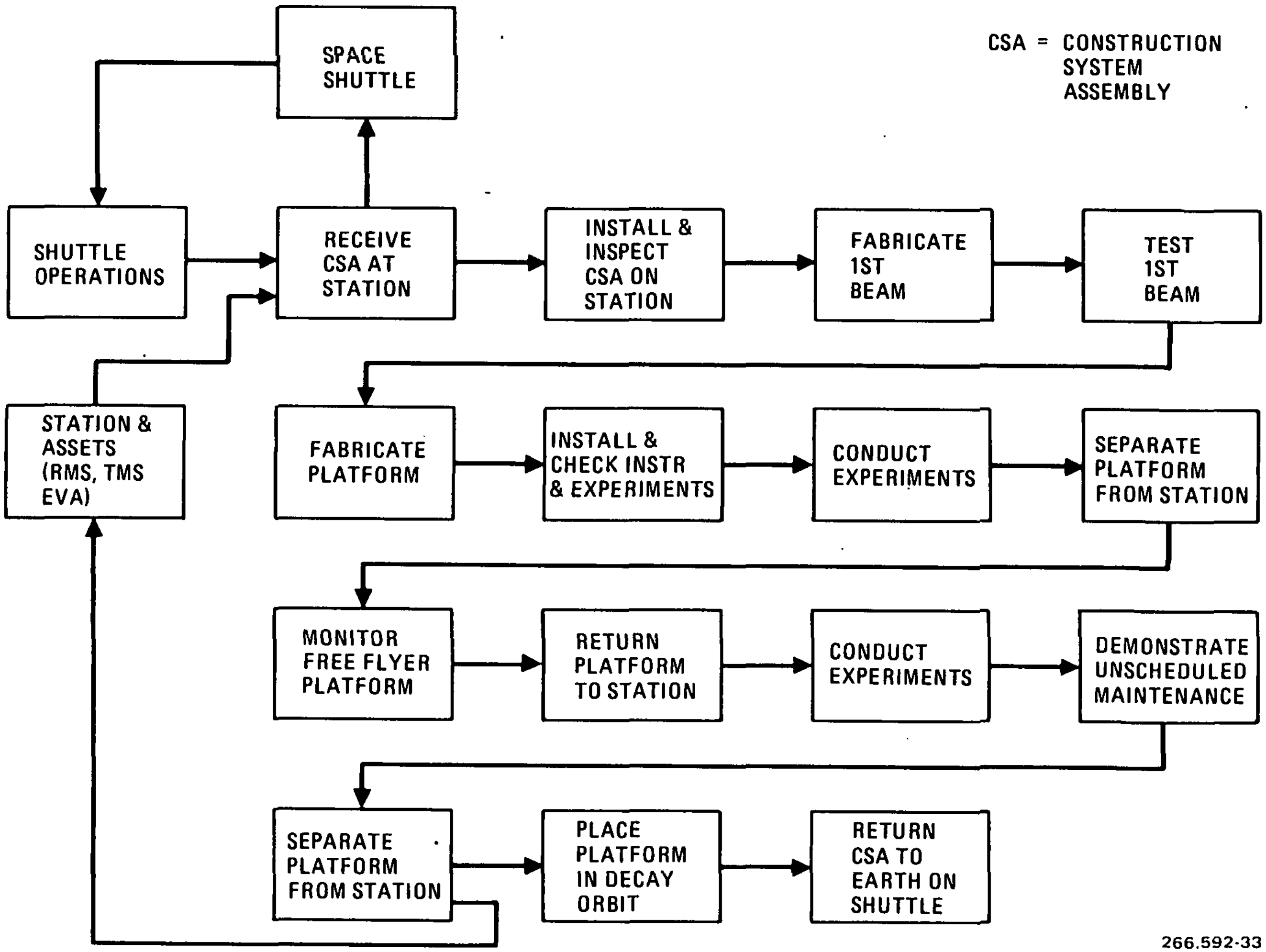

Figure 2-34. Large Space Structures Construction Operations

Figure 2-35. Large Space Structures Construction Operations

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2.2.5.2 Space Station Equipment Requirements. The space structure construction project is accommodated on station with minimal impact on planned station assets. The Space Station provides the necessary support structure and mounting provisions required to host the construction system assembly. A station RMS equipped with television and adequate lighting are available for equipment handling and transfer operations. A TMS is used to maneuver the completed platform structure during the free flight phase of the experiment and for insertion of the platform into the final delay orbit. A direct viewing port and strategically placed closed circuit television system with distributed illumination are essential for equipment observations and inspection.

The Space Station to construction system assembly interface is shown in Figure 2-36. In this configuration, a station general purpose computer and associated bus network perform all executive control and functions required for construction system assembly operation. Data display control and command initiation are accomplished via a Space Station multifunction control and display system (MCDS) or by dedicated experiment control panels. The dedicated control panels would be used for functions requiring quick reaction in response to real time visual observtion. The panels interface with the general purpose computer. Separate caution and warning (C&W) signals and safing commands interface with station control. A set of interfaces to accommodate video signal data from TV monitors located in the assembly jig or beam builder subassemblies of the CSA are indicated. Electrical power is supplied from a Space Station power source.

2.2.6 MAN-OPERATED MISSION CREW REQUIREMENTS. Man-operated missions summarized in Table 2-1 have been identified in a variety of fields or disciplines which include:

- Astrophysics
- Earth and Planetary Exploration
- Environmental Observations
- Life Sciences
- Materials Processing
- Earth and Ocean Observations
- Communications
- Industrial Services

The skill requirements for each mission was established using the limited information available at this stage of planning. The skill requirements have been categorized into seven skill types and three skill levels as shown in Table 2-23.

As shown in Figure 2-37 the number of missions vary from year to year. Also shown is the number of new missions started by years. These missions are of varying lengths. Some missions lasting only a few days while others have a lifetime of several years.

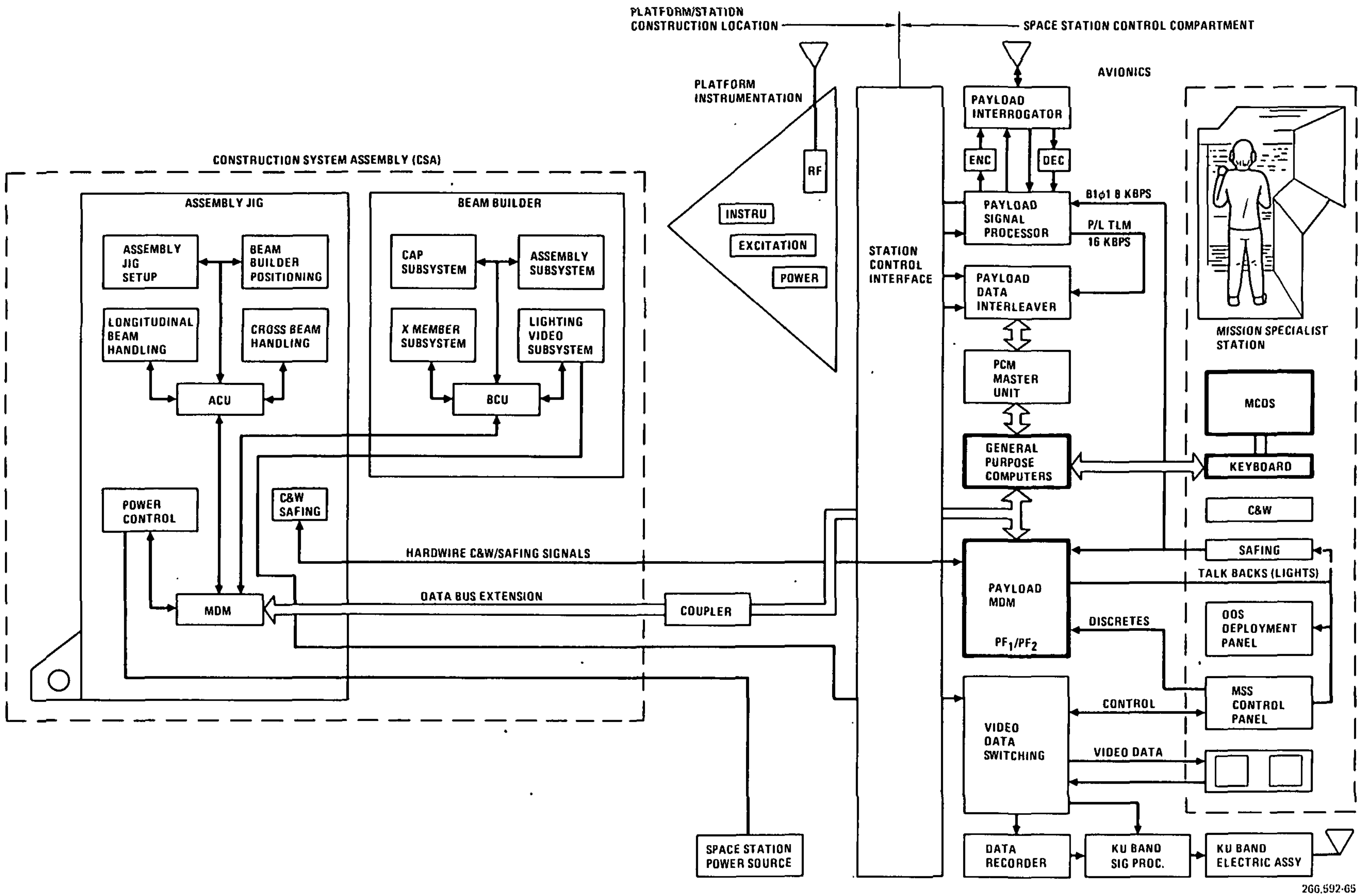

Figure 2-36. Space Station/CSA and Platform

Table 2-23. Crew Skill Categories

SKILL TYPE

- No special skill required
- Medical/Biological
- Physical Sciences
- Earth and Ocean Sciences
- Engineering
- Astronomy
- Spacecraft Systems

SKILL LEVELS

- Task Trainable
- Technician
- Professional

The missions also vary in the amount and frequency of man's involvement. Some tasks will need monitoring on a continual basis while others will only require periodic maintenance or servicing.

This variance in task length and frequency will require flexibility in the scheduling of work.

Due to the fluctuation of skills and time required at any one time, the crew will be cross trained to perform tasks in several areas.

The skill type and level for the identified man-operated missions along with the crew time requirements to support these missions are presented in Table 2-24. This data shows the change in crew skill requirements through the year 2000.

2.2.7 STATION CREW OPERATIONS MANAGEMENT REQUIREMENTS. This subsection identifies the requirements that govern the actions and activities of the crew to maintain a safe, working and efficient Space Station in cooperation with ground support operations.

2.2.7.1 Station Management/Scheduling/Activity Planning. Management of the Space Station, its systems and operations is a critical function. The Space Station commander will be in charge of this function during the mission. Station management tasks include:

- Directing and monitoring all station operations
- Coordinating the crew's daily activities
- Monitoring and scheduling of all station and system maintenance
- Maintaing health and well being of the crew
- Coordinating the delivery and use of all supplies and spares

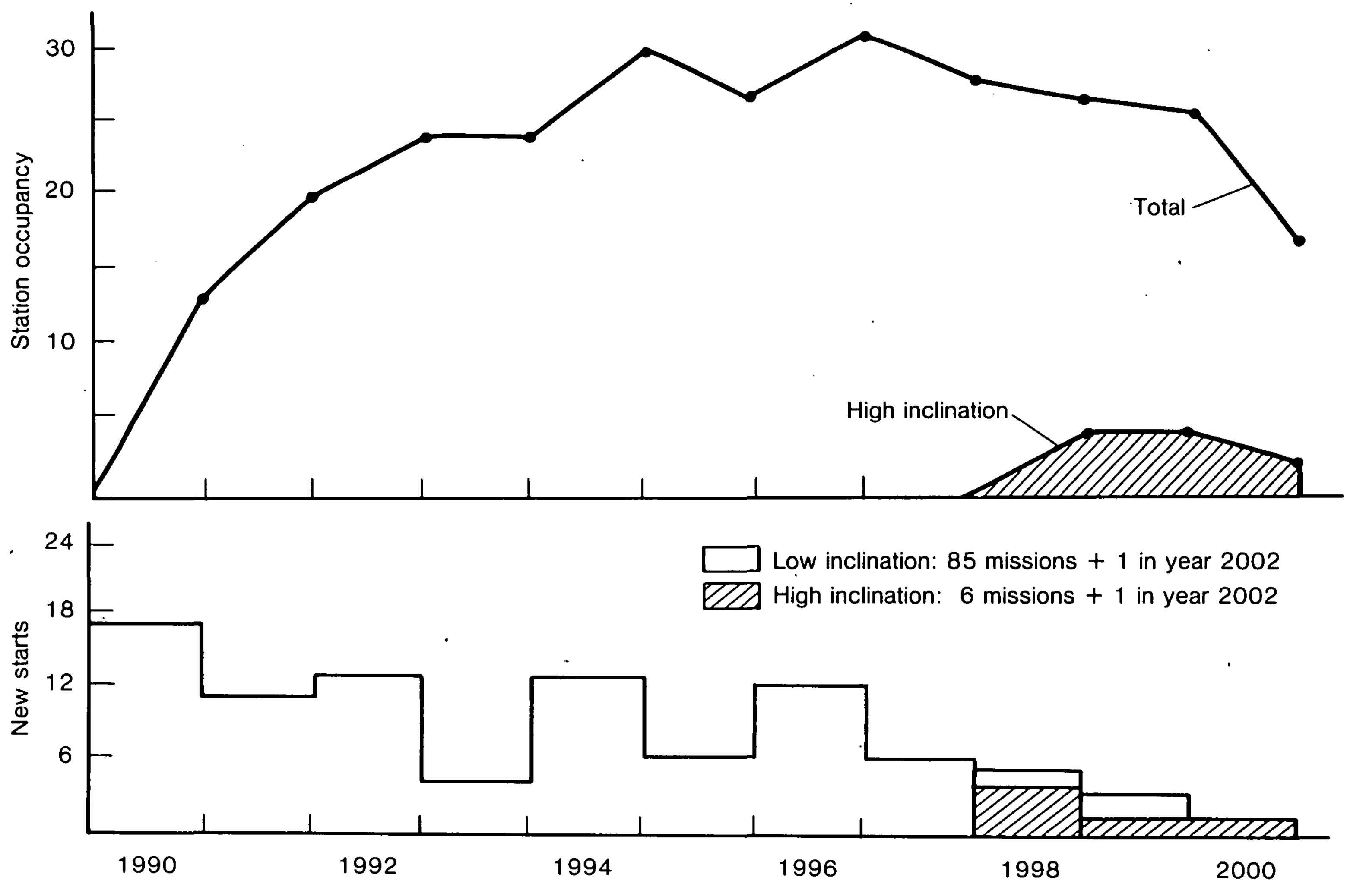

Figure 2-37. Baseline Time-Phased Mission Set Man-Operated Missions

Table 2-24. Crew Time Requirements by Skill Type and Level

DISCIPLINES	SKILL TYPE AND LEVEL	CREW TIME REQUIREMENTS (HOURS PER DAY)										
		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ASTROPHYSICS	ASTRONOMY TECHNICIAN	0.5	0.5	2.5	3	3	0.5	1.2	1	0.5	1	1
LIFE SCIENCE	MED./BIOL. – TASK TRAINABLE	2	2	2	2	2	2	2	2	2	2	2
	MED./BIOL. – TECHNICIAN	7	7	7	7	7	7	9.5	9.5	9.5	9.5	9.5
	MED./BIOL. – PROFESSIONAL	7	7	7	7	7	7	7	7	7	7	7
	ENGINEERING – PROFESSIONAL			1	1	1	1	1	1			
	SPACE CRAFT SYSTEMS – TASK TRAINABLE							0.25	0.25	0.25	0.25	0.25
	SPACE CRAFT SYSTEMS – TECHNICIAN	0.25	0.75	1.25	1.25	1.25	1.25	5.25	5.25	4.75	4.75	4.75
	SPACE CRAFT SYSTEMS – PROFESSIONAL		0.5	1	1	1	1	0.1	0.1	0.5	0.5	0.5
MATERIALS PROCESSING	MED./BIOL. – TECHNICIANS			2	2		4	4	4	4	4	4
	MED./BIOL. – PROFESSIONAL	1	1	3	2	2	6	6	6	6	6	6
	ENGINEERING – TECHNICIAN	2	2	2		10	10	10	12	12	12	12
	ENGINEERING – PROFESSIONAL	1	1	1		8	8	8	10	10	10	10
TECHNOLOGY DEVELOPMENT	NO SKILL – TECHNICIAN	0.3	1.0	2.2	0.6	0.8	0.8	1.4	0.6	0.6	0.6	
EARTH AND PLANETARY EXPLORATIONS	EARTH & OCEAN SCIENCE – PROFESSIONAL		0.25	0.95	0.7	0.5	0.5					
	ENGINEERING – TECHNICIAN							0.2	0.2	0.2		
	ENGINEERING – PROFESSIONAL			0.5	0.5	0.5	0.75	0.25				
ENVIRONMENTAL OBSERVATIONS	PHYSICAL SCI. – TECHNICIAN									0.25	0.25	
	EARTH & OCEAN – PROFESSIONAL					0.4	0.4		0.25			
	ENGINEERING – TECHNICIAN	0.2			0.4			0.5	0.25	0.5	0.25	0.25
	ENGINEERING – PROFESSIONAL					0.4	0.4					

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Although the mission requirements are established early in the design and operations planning stage of the Space Station development and work schedules will have been designed to meet these requirements, the scheduling of all tasks should be flexible. This will allow for contingency activities such as unforeseen maintenance, a crewmember's illness, or the collection of data from unexpected events.

It has been shown by numerous studies that mental health problems and stress are related to a lack of participation in decision making, a lack of control of work or a lack of autonomy. This would suggest the need for the total crew to be involved, to some extent, in the planning of Space Station activities.

2.2.7.2 Crew Work/Rest/Sleep/Cycle. The highest human performance efficiency exists where a stable 24 hour period of work and rest is mandatory, with the critical factor being the sleep/rest cycle and the 24 hour period being the generally accepted circadian rhythm.

The nominal work schedule selected for the Space Station for a 90 day tour of duty includes a seven day work week (6 days of work, one day off) with a daily work shift of 8 hours. The 24 hour crew work/rest/sleep cycle has been allocated as follows.

• Work	8 hours
• Daily housekeeping	1 hour
• Meal preparation/eating	2.5 hours
• Pre and Post-sleep activities	1.5 hours
• Recreation, medical & Exercise (includes up to one hour as a human research subject)	3.0 hours
• Sleep	8 hours

Crew members will probably work and sleep in shifts as required to meet the mission schedule requirements, although there are some disadvantages associated with shift work. These disadvantages include:

- Several weeks of adaptation to changes in the sleep/work cycle
- Possible desynchronosis may result, the symptoms of which include:
  - Insomnia
  - Appetite loss
  - Nervous stress
  - Inability to work
- Interference with sleep/rest cycle of other crew members
- Lack of social interaction and communication among and between the total crew creating a potential for distrust, suspicion and hostility.

2.2.7.3 Scheduled/Unscheduled Station System Maintenance. The scheduled Space Station maintainability/reliability requirements will be established through the development of the required systems and subsystems. Once they are established, valid numbers and types of replacement and repair parts will be determined.

Long life Space Station reliability can be practically achieved by use of space maintainable hardware augmented by in-flight spares. On board systems will require automated check-out, monitoring, warning and fault isolation to preclude degradation of overall operations, and critical delays in missions operations.

The crew will be responsible to maintain, replace and/or repair all equipment to the lowest practical level. Due to excessive crew training, spares inventory and special tool requirements it is, with few exceptions, not considered practical to perform maintenance below the component level except in emergencies.

As a basis of allocating time for maintenance operations a figure of 16 hours per week total is used as a reference point. This is derived by assuming certain replacement activities may be scheduled for one or more of the equipments over a 90-day cycle. Averaged over a one week cycle, this would total approximately 8 hours, but allowing for contingency factors such as unscheduled maintenance activities might require an additional eight (8) hours per week. This allocated time for scheduled and unscheduled maintenance is included in the computation of crew size as part of the station operation activities.

2.2.7.4 Station Housekeeping/Inventory Management Tasks. The station housekeeping and inventory management will be performed by the crewmembers. These tasks involve the following:

- Stocking and stowing of food supplied
- Changeout of consumables such as LIOH cannisters
- Resupply or cleaning of clothing
- Collection and disposal of refuse
- Cleaning of habitat and personal hygiene areas
- Management of water system and ECLSS
- Performing routine maintenance

A time allocation to perform these tasks of up to one hour per day per crew member was used in computing the crew size requirement.

2.2.8 SERVICING OPERATIONS REQUIREMENTS. To determine the crew man-year requirements and equipment needed for the servicing operations an operational activities analysis was performed. The process used is illustrated in Figure 2-38.

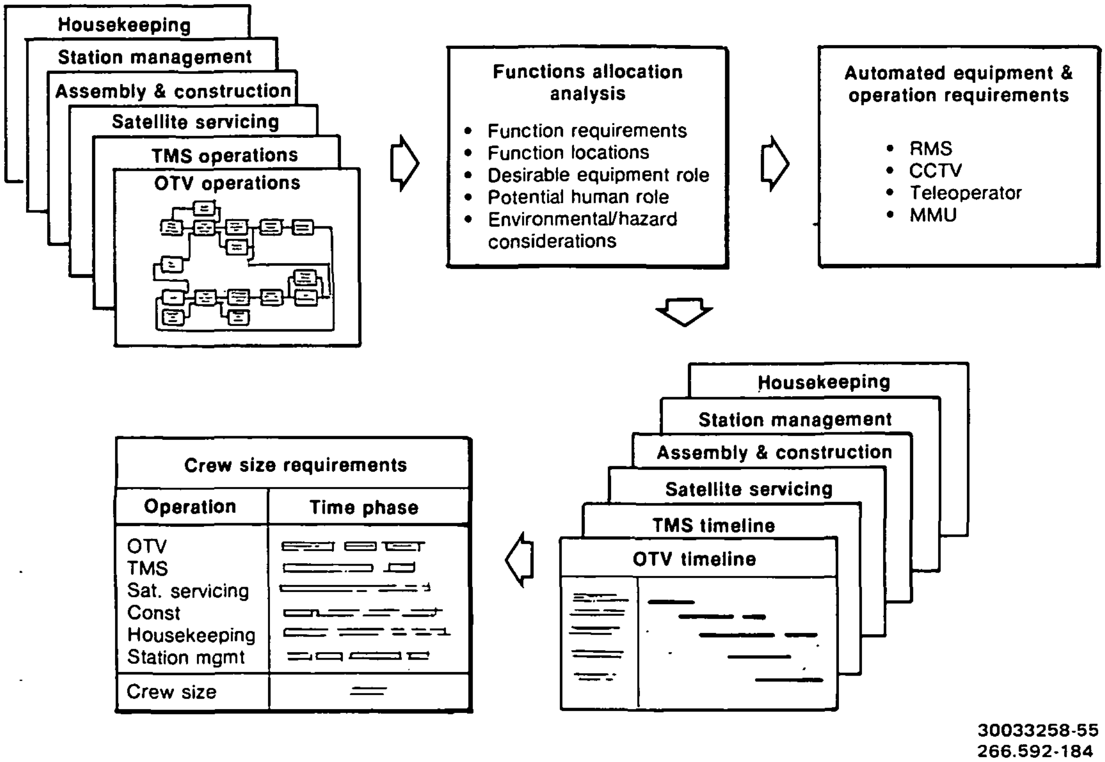


Figure 2-38. Operational Activities Analysis

Using the functional flow diagrams that are presented in Subsections 2.2.1 thru 2.2.5, a functions allocation analysis was performed for a typical mission for each operation. The operations established for these missions included such factors as scheduled or routine maintenance, single payload delivery or retrieval, and the modular design of the OTV, TMS and satellites. These missions considered only the functions to be performed by the Space Station crew. All operations performed away from the Space Station were assumed to be primarily supported by ground operations. This included the launch of the OTV or TMS as well as the delivery, retrieval or in-situ maintenance of free-flyers.

The functions alloction analysis performed on each mission considered such factors as:

- Function requirements
- Function location
- Desirable equipment role
- Support equipment
- Potential human role
- Environmental/hazard considerations
- Man's location
- Function duration
- Crew size per function

The functions allocation analysis is summarized in Tables 2-25 through 2-27.

The definitions as shown in Table 2-28 of tasks to be performed by man, man/-machine, and machine only were adopted for the functions allocations analysis.

The principal criteria and the philosophy used in the functions allocation analysis for assigning space station activities to man, man/machine or machine only are presented in Table 2-29.

2.2.8.1 Crew Tasks and Skill Requirements. The crew will be responsible for carrying out the functions assigned to man in the function allocation analysis that was presented in the preceding subsection. The primary operations include OTV, TMS and satellite servicing; payload assembly and integration; and support activities. The functions associated with these operations are to:

a. Change out parts.

b. Replenish consumables.

c. Reconfigure.

d. Determine maintenance requirements.

e. Operate support equipment.

f. Control berthing and docking operations.

g. Schedule all related tasks.

Satellite deployment, retrieval, in-situ servicing, and other off-Station missions are not included in the functions of the Space Station. These activities will be controlled by ground operations with the Space Station performing minimum monitoring and contingency operations. This will allow the crew to perform tasks which cannot be accomplished by ground operations.

There will be other periodic tasks which are not included at this time. These tasks could be performed by the Orbiter crew or a temporary crew especially trained for the task. These activities include such missions as assembly and construction of large structures.

The crew should be trained in all the basic functions associated with these operations. Due to the mission numbers the crew will be multidisciplined and require cross training. The crew will be provided with specific repair procedures for each piece of equipment and will be trained to perform the tasks using both automation and EVA procedures. The understanding of electronics and mechanical equipment are the most critical crew skills. The EVA crewman will need the physical skills to handle tools and to perform fine manipulative tasks.

2.2.8.2 Equipment Requirements. For each function identified in the functions allocation analysis, the desired equipment role was determined and the support equipment required to achieve these roles were identified. The desired equipment role and support equipment were presented in Tables 2-25 through 2-27. Listings of the support equipment and facilities for the servicing operations are located in Subsections 2.2.1 through 2.2.5.

Table 2-25. OTV Payload Delivery Functions Allocation Analysis

Operations: OTV PAYLOAD DELIVERY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Rotate OTV and Lock	Position OTV for entry into maintenance module to allow extension of shelter	OTV M/D area	Automatic control of OTV rotation, Perform automatic hold down function	Automatic Rotating mechanism, mobile berthing carriage, Automatic hold down latch, CCTV System	OTV M/D Area, Control Center	Activate and monitor operation		Control Center	45 min	1
Move OTV to Maintenance Module	Provide IVA access to OTV Avionics	Maintenance Module, OTV M/D area	Translate OTV and provide pressure seal with maintenance module	Mobile berthing carriage, Maintenance Module airlock interface, Maintenance module	Maintenance Module, OTV M/D area	Operate, control, and monitor translation and pressurization operations	Air leak	Control Center	1 hr.	1
Extend Shelter	Position shelter to cover OTV	OTV M/D area	Provide shelter mobility and control	Track and drive mechanism and control, CCTV system, Viewing port	OTV M/D area, Control Center	Activate and monitor shelter movement		Control Center	15 min.	1
Visual Inspection	Identify physical damage	OTV M/D area	Provide adequate visual field of view and resolution capabilities	CCTV System	OTV Maintenance area, Control Center	Monitor visual presentation and provide inspection analysis		Control Center	2 hrs.	1
Reduce Flight Data	Identify Equipment failure	OTV	Provide OTV built-in failure detection and fault isolation capabilities	Computer System	Control Center, Maintenance Module	Activate and control system, Evaluate output		Control Center, Maint. Module	30 min.	1
Perform Scheduled Maintenance	Perform routine servicing, inspection, checkout, some related remove and replace tasks	OTV Maintenance area, Maintenance Module	OTV Modular Construction to facilitate remove & replace, Automatic test and fault isolation capabilities, provide remote replacement capabilities	Remote Manipulator, CCTV System, various tools, parts and supplies, maneuvering device, viewing port, computer system	OTV maintenance area, Tool/Supply Storage area, Control center maintenance module	Activate, monitor, control and provide IVA & EVA component replacement capabilities	EVA inherent hazards	Control Center	8 hrs.	2
Systems Operational Testing	Assure operational readiness of OTV Equipment	OTV Maintenance module control center	Automatic equipment operation and failure detection	Computer System, OTV built-in test, data link	OTV maintenance module control center	Activate and monitor test process		Control Center	2 hrs.	1
Retract Shelter	Remove shelter to expose OTV	OTV M/D area	Provide shelter mobility and control	Track and drive mechanism and control, CCTV system, viewing port	OTV D/M area, Control Center	Activate and monitor shelter movement		Control Center	15 min.	1

Table 2-25. OTV Payload Delivery Functions Allocation Analysis, Contd

Operations: OTV PAYLOAD DELIVERY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Retract OTV from Maintenance module and rotate	Position OTV prior to payload mating operations and propellant transfer	OTV M/D area	Provide mobility to translate OTV, Automatic control of OTV rotation	Mobile berthing carriage and track structure, automatic rotating mechanism CCTV system	OTV M/D area, Control Center	Activate and monitor operation		Control Center	1 hr	1
Move to propellant transfer position	Position for fluid line interface	OTV M/D area	Provide mobility to translate OTV	Mobil berthing carriage and track structure, CCTV system	OTV M/D area, Control Center	Operate, control and monitor OTV translation		Control Center	15 min.	1
Engage Propellant Transfer Interface and verify	Provide adequate fluid line continuity and verify interface	OTV M/D area	Automatic quick disconnect capability with interface check capability	Automatic disconnect panel, CCTV system Propellant sensor equipment, computer control system	OTV M/D area	Activate automatic process and monitor sequence and sensor detection	Propellant Leak	Control Center	15 min	1
Transfer Payload	Transfer payload to OTV vehicle area and position for mating	Payload and OTV M/D area	Provide automatic payload handling & transport ability provide universal grapple fixture	RMS with end adapters, control panel, viewing port, CCTV system	On maintenance shelter, Control Center	Operate and monitor transfer operations	Possible collision	Control Center	45 min.	2
Mate Payload and OTV	Secure payload to OTV and verify operational interfaces	OTV M/D area	Universal automatic interface provided on payload, automatic interface latch system, built-in automatic interface test	CCTV system built-in automated test equipment, computer system, RMS	OTV, Control Center	Operate, monitor and control of payload to OTV integration operation		Control Center	2 hrs.	2
Prepare Payload	Prepare payload for launch and verify all systems	OTV M/D area, payload	Mission peculiar may include deployment of antenna and appendages and verify all systems	RMS, CCTV system, payload built-in test set, computer system	Paylaod OTV M/D area	Activate and monitor operations		Control Center	up to 1 hr.	2
Transfer Propellant to OTV	Transfer propellant from propellant storage facility to OTV	OTV M/D area, propellant storage facility	Chill down, monitor and transfer propellent	Propellant storage facility control equipment and transfer lines	Propellant storage facility, Control Center, OTV M/D area	Activate, monitor and provide intervention control of operations	Proellant Leak	Control Center	6 hrs.	1
Leak check	Monitor for propellant leaks	OTV M/D area OTV propellant system	Detect propellant leakage and identify leakage location	Leak sensors and monitor equipment	OTV M/D area, Control Center	Monitor and provide intervention control of operations	Propellant Leak	Control Center	6 hrs.(Perform simultaneously with Propellant Trans.	1
Perform prelaunch operations/countdown	Verify systems operation readiness and position for launch	OTV M/D area	Measure system component readiness, provide mobility to translate OTV	Computer system, built-in test set, mobile berthing carriage and track system	OTV M/D area	Activate, monitor and verify operations		Control Center	2 hrs.	2

Table 2-25. OTV Payload Delivery Functions Allocation Analysis, Contd

Operations: OTV PAYLOAD DELIVERY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Bring System on Line	Verify Control Center Systems Operational readiness	Control Center	Perform automatic self test of operating equipment	Control Equipment Panels, RMS CCTV system, Data Link, and Communications Computer Systems Automatic Test Equipment	Control Center OTV Maintenance Docking Area	Activate & Control Station equipment to be used in docking Operate Computer System Monitor test results and correct anomalies	Zero-G environment	Control Center	1 hr (Perform simultaneously with Docking Preparation	1
Docking Preparation	Prepare Docking facilities for OTV arrival Verify OTV location and arrival time	OTV Docking area Control Center	Self-test verification of docking facilities	CCTV system Computer System Control Panels RMS, data link, Berthing Structure & Control Shelter and Control	OTV Maintenance/Docking Area Control Center	Operate/Monitor CCTV Operate & monitor equipment and position for docking		Control Center	1 hr	1
Dock OTV	Position, Stabilize and Capture OTV	OTV Maintenance/ Docking (M/D) area	Automatic Rendezvous RMS Control of Docking arm engagement capability CCTV observation & Inspection	Rendezvous Target reflector RMS or docking arm Viewing Port, CCTV System Computer System	OTV OTV Maintenance Docking area Control Center	Operate, monitor, and control Docking Process	Possible collision	Control Center	30 min.	2
Berth and Position for Propellant transfer	Secure OTV in Berthing Structure Position for fluid line interface	OTV M/D area	Perform automatic Berthing latch function Provide mobility to translate OTV	Computer System Berthing Structure Automatic Berthing Latch mechanisms, mobile berthing structure.	OTV M/D area Control Center	Operate, control and monitor Berthing process		Control Center	30 min.	2
Engage Propellant Transfer Interface and Verify	Provide adequate fluid line, continuity and verify interface	OTV M/D area Specifically OTV Berthing interface	Automatic quick disconnect capability with interface check capability	Automatic disconnect panel, CCTV, Propellant Sensor equipment, Computer Control System	OTV M/D Area Specifically OTV Berthing interface, Control Center	Activate Automatic process and monitor sequence and sensor detection	Propellant Leak	Control Center	15 min.	1
Leak Check	Monitor for propellant leaks	OTV M/D area Interface & OTV Propellant System	Detect propellant leakage & Identify Leakage location	Leak sensors and monitor	OTV M/D Area Control Center	Monitor and provide intervention control of operations	Propellant Leak	Control Center	4 hr. (Perform simultaneously with Propellant Transfer	1
Transfer Propellant	Transfer propellant from OTV to propellant storage facility	OTV M/D area, Propellant Storage Facility	Chill down, monitor and transfer propellant	Propellant Storage Facility, Control Equipment Transfer Lines	Propellant Storage facility, Control Center, OTV M/D area	Activate, monitor, and provide intervention control of operations	Propellant Leak	Control Center	4 hr	1
Disengage Propellant Transfer Interface and Verify seals	Provide Adequate fluid line continuity and verify interface	OTV M/D area Specifically OTV Berthing interface	Automatic quick disconnect capability with interface check capability	Automatic disconnect panel, CCTV System Propellant Sensor equipment, computer control system	OTV M/D area Specifically Berthing Structure and interface, Control Center	Activate process and monitor sequence and sensor detection	Propellant Leak	Control Center	30 min.	1

Table 2-25. OTV Payload Delivery Functions Allocation Analysis, Contd

Operations: OTV PAYLOAD DELIVERY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Launch Phase I	Release OTV from Space Station	OTV Docking area	Automatic release of OTV from Space Station	Automatic release mechanism	OTV Docking Interface	Activate and monitor operations	Possible collision	Control Center	Momentarily	1
Deploy and drift	Position OTV away from Space Station for launch	Not on Station	Provide adequate visual field of view & resolution capabilities	CCTV system	Space Station exterior	Monitor OTV Drift	Possible collision	Control Center	30 mins	2
Post Launch - Space Station secure	Secure all systems	Control Center, OTV Docking area	Perform automatic shut down	Control Panel	Control Center	Monitor and checkout the secure operation		Control Center	1 hr.	2

*All activities are performed in a zero-g environment

Table 2-26. Satellite Servicing Functions Allocation Analysis

Operations: SATELLITE SERVICING

SATELLITE - 2

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Perform Systems Test	Identify equipment failure	Satellite	Provide satellite built-in failure detection and failure isolate	Computer system satellite built-in test	Satellite servicing area, Control Center	Activate and monitor test process and evaluate output		Control Center	1 hr	1
Retract Shelter	Position shelter to expose satellite	Satellite servicing area	Provide shelter mobility & control	Track & drive mechanism CCTV system viewing port	Satellite servicing area	Activate and monitor shelter movement		Control Center	15 min	1
Perform Satellite Operational Test	Assure operational readiness of satellite equipment	Satellite servicing area	Provide automatic equipment operation and failure detection	Computer system OTV built-in test, data link	Satellite servicing area	Activate and monitor test process		Control Center	up to 6 hrs	1
Grasp satellite and release from maintenance pedestal	Prepare satellite for transfer to OTV/TMS	Satellite servicing area	Provide universal grapple fixture, automatic latch function	RMS with end adapter, control panel, viewing port, CCTV system, automatic latch	Satellite servicing area	Operate and monitor grasping operation		Control Center	15 min	1

*All activities are performed in zero-g environment

Table 2-26. Satellite Servicing Functions Allocation Analysis, Contd

Operations: SATELLITE SERVICING

SATELLITE - 1

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Visually inspect interface	Identify physical damages	Satellite Servicing area	Provide adequate visual field of view & resolution capabilities	CCTV system	Satellite servicing area	Monitor visual presentation and provide inspection analysis		Control Center	15 min	1
Position satellite on maintenance pedestal	Position for interface connect and to secure	Satellite servicing area	Provide mobility of satellite, universal alignment capability, and universal umbilical interface	RMS, maintenance pedestal with rotation capability, universal umbilical interface and alignment equipment, CCTV system	Satellite servicing area	Monitor, control and verify positioning operation	Possible collision	Control Center	15 min	
Engage and latch satellite to maintenance pedestal & verify	Secure satellite to maintenance pedestal and verify interface	Satellite servicing area	Provide automatic latch function, universal umbilical interface, automatic interface check capabilities	Maintenance pedestal with automatic latch mechanism, universal umbilical interface, computer system, CCTV system, leak sensors	Satellite servicing area	Activate, monitor and control sequence		Control Center	15 min	1
Extend shelter	Position shelter to cover satellite	Satellite servicing area	Provide shelter mobility & control	Track & drive mechanism CCTV system viewing port	Satellite servicing area	Activate and monitor shelter movement		Control Center	15 min	1
Perform visual inspections	Identify physical damage	Satellite servicing area	Provide adequate visual field of view & resolution capabilities	CCTV system	Satellite servicing area	Monitor visual presentation and provide inspection evaluation		Control Center	1 hr	1
Perform System Test	Identify equipment failure	Satellite	Provide satellite built-in failure detection and failure isolate	Computer system satellite built-in test	Satellite servicing area	Activate and monitor test process, and evaluate output		Control Center	2 hrs	1
Prepare Maintenance Plan	Prepare plan to schedule maintenance and support activities	Control Center	Provide information on available parts and support equipment availability	Computer System	Control Center	Activate, monitor and control operation to compile maintenance schedule		Control Center	30 min	1
Perform scheduled maintenance tasks	Perform routine servicing, checkout, some related remove & replace tasks	Satellite servicing area	Satellite modular construction to facilitate remove & replace, automatic test & fault isolation capabilities, provide remote replacement capabilities	RMS, CCTV System, various tools, parts/supplies, maneuvering device, computer system	Satellite servicing area, tool/supply storage area	Activate, monitor control & provide IVA & EVA component replacement capabilities		Control Center (possible EVA)	4 to 16 hrs	2

Table 2-27. TMS - Payload Retrieval and Deploy Functions Allocation Analysis

Operations: TMS - PAYLOAD RETRIEVAL & DEPLOY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Bring system on line	Verify control center systems readiness	Control Center	Perform automatic self test of operating equipment	Control Equipment Panels, RMS, CCTV System, data link, communications, computer system, automatic test equipment	Control Center, TMS M/D area, Payload maintenance area	Activate and control system equipment to be used in docking and payload transfer, operate computer, monitor test results and correct anomalies		Control Center	1 hr. (perform simultaneously with docking preparations)	1
Docking preparation	Prepare docking facilities for TMS arrival Verify TMS location/ arrival time	TMS Docking area, Control Center, Payload servicing area	Self test verification of docking facilities	CCTV system, computer system, control panels, RMS, data link	TMS docking area, Control center, payload servicing area	Operate and monitor equipment and position for docking		Control Center	1 hr.	1
Capture payload and release TMS	Position, stabilize, and capture payload. release TMS	TMS/payload capture and TMS release	Automatic Rendezvous, payload capture and TMS release	RMS, CCTV, Rendezvous target reflector, Automatic release mechanism	Space Station	Activate, control and monitor operations	Possible collision	Control Center	1 hr.	2
Dock TMS	Position, stabilize and capture TMS	TMS Docking area	Automatic rendezvous, RMS control of docking or docking arm engagement capability. CCTV observation & inspection	Rendezvous target reflector, RMS or docking arm, viewing port, CCTV system, computer system.	TMS, TMS docking area, Control Center	Operate, control and monitor docking process	Possible collision	Control Center	30 min.	2
Secure TMS	Secure TMS in Maintenance area	TMS docking & maintenance area	Perform automatic berthing latch function	Computer system, automatic latch mechanism, berthing dock	TMS Maintenance area	Operate, control and monitor berthing process		Control Center	15 min.	1
Transfer and berth Payload	Transfer payload to servicing area, position and secure	Payload servicing area	Provide automatic payload handling and transportability, automatic berthing latch function	Computer System, automatic latch mechanism, berthing area, RMS	Payload Servicing area	Operate and monitor transfer operations	Possible collision	Control Center	45 min.	2
Check Interface TMS/Space Station	Verify Interface	TMS Maintenance area	Provide automatic interface Check capability	Automatic interface check leak sensors	Control Center, TMS Maintenance area	Operate and monitor interface verification		Control Center	30 min.	1
Visual Inspection	Identify Physical damage	TMS Maintenance area	Provide adequate visual field of view and resolution capabilities	CCTV System	TMS Maintenance area, Control Center	Monitor visual presentation and provide inspection analysis		Control Center	2 hrs.	1

Table 2-27. TMS - Payload Retrieval and Deploy Functions Allocation Analysis, Contd

Operations: TMS-PAYLOAD RETRIEVAL & DEPLOY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Initiate Battery Conditioning	Start battery recharge process		Provide automatic battery recharge process	Atuomatic hookup and power lines	TMS Maintenance Area	Activate and monitor battery recharge process		Control Center	Initiate (Monitor for 24 + hrs.)	1
Data Reduction	Identify Equipment failure	TMS	Provide OTV built-in failure detection and fault isolation	Computer System	Control Center	Activate and control system and evaluate output		Control Center	30 min.	1
Scheduled Maintenance	Perform route servicing, inspection, checkout, and some related remove and replace tasks	TMS Maintenance area	TMS Modular construction to facilitate remove and replace, automatic test and fault isolate capabilities, provide remote replacement capabilities	Remote Manipulator, CCTV system, various tools, parts and supplies, maneuvering device, viewing port, computer system	TMS Maintenance area, Tool/Supply Storage area, Control Center	Activate, monitor control and provide IVA & EVA component replacement capabilities	EVA Inherent hazards	Control Center (possible EVA)	8 hrs.	2
Operational checkout	Assure operational readiness of TMS equipment	TMS, Control Center	Automatic equipment operation and failure detection	Computer System, TMS built-in test, data link	TMS, Control Center	Activate and monitor test process		Control Center	1 hr.	1
Refuel	Transfer Propellant from propellant storage facilities to TMS	TMS Maintenance area, propellant storage facility	Monitor and transfer propellant	Propellant storage facility control Equipment and Transfer lines	Propellant storage facility, TMS Maintenance area, Control area	Activate, monitor and provide intervention control of operations	Propellant leak	Control Center	4 hrs.	1
Assemble TMS Mission Configuration	Assemble special equipment for TMS mission	TMS Maintenance area	Mission Peculiar (Transfer, position mate and verify any special equipment to complete mission)	RMS, CCTV system, built-in test set	TMS Maintenance area	Activate, monitor and verify assembly operations	Possible collision	Control Center	up to 4 hrs.	2
Transfer satellite	Transport payload to TMS maintenance area and position for mating	Satellite and TMS maintenance area	Provide automatic payload handling and transport ability	RMS with end adapters, control panel, viewing port, CCTV system	TMS maintenance area and Control Center	Operate and monitor transfer operations	Possible collision	Control Center	30 min.	2
Mate Satellite to TMS	Secure satellite to TMS	TMS Maintenance area	Universal automatic interface provided on satellite, automatic interface latch system	CCTV system, equipment, computer system, RMS	TMS, Control Center	Operate, monitor and control satellite and TMS integration operations		Control Center	2 hrs.	2
Final Checkout	Verify operational interfaces of satellite and TMS	TMS Maintenance area	Built-in automatic interface test.	Built-in automated test equipment, computer system	TMS, Satellite	Activate and monitor test process		Control Center	1½ hrs	2

Table 2-27. TMS - Payload Retrieval and Deploy Functions Allocation Analysis, Contd

Operations: TMS- PAYLOAD RETRIEVAL & DEPLOY

FUNCTION TITLE	FUNCTION REQUIREMENT	FUNCTION LOCATION	DESIRABLE EQUIPMENT ROLE	SUPPORT EQUIPMENT	EQUIPMENT LOCATION	POTENTIAL HUMAN ROLE	ENVIRONMENTAL HAZARD CONSIDERATION*	MAN'S LOCATION	FUNCTION DURATION	CREW SIZE
Pre-mission Operations/ Countdown	Verify systems operation readiness and position for Launch phase 1	TMS Maintenance area	Measure system component readiness, provide transfer & capability of TMS	Computer system, built-in test set, RMS and end adapter	TMS Maintenance	Activate, monitor and verify operations		Control Center	1½ hrs.	2
Launch Phase 1	Release TMS from Space Station	Secured by RMS away from station	Automatic release of TMS from RMS	Automatic release mechanism	TMS/RMS Interface	Activate and monitor operation	Possible collision	Control Center	momentarily	1
Deploy and Drift	Identify when TMS is positioned for launch	Not on station	Provide adequate visual field of view and resolution capabilities	CCTV System	Space Station Exterior	Monitor TMS Drift	Possible collision	Control Center	30 min.	2
Post launch Space Station Secure	Secure all systems	Control Center, TMS Maintenance area	Perform automatic shut down	Control Panel	Control Center	Monitor and checkout the secure operations		Control Center	1 hr	2

*All activities are performed in zero-g environment

Table 2-28. Man-Machine Task Definitions

TERM	DEFINITION
Man	Task is performed completely by humans or by humans with hand-held tools between them and task object (IVA and EVA)
Man/Machine	Task is performed by humans with manually operated or programmable machines, one complementing the other (IVA and EVA). This includes RMS, interactive computers, etc.
Machine Only	Tasks performed exclusively by computers, teleoperators, automata, robots (with human supervision.)

From "The Human Role in Space" by Stephen B. Hull, Georg Von Tresenhausen, and Gary W. Johnson, NASA Technical Memorandum, NASA TM:82482, April 1982.

Table 2-29. Critieria For Assigning Tasks to Man or Machines

CRITERION	PHILOSOPHY
Task Location	Remote or hard to access task should be assigned to man-machine or machine only.
Task Frequency	Frequently occurring and routine tasks will be performed by man/machine or machine only.
Task Duration	All EVAs are limited to 8 hours/day/crewmember. A short performance time for a task outside station should be performed by man/machine or machine only. If task time is greatly reduced by use of man or machine, then assign accordingly.
Complexity of Task	Assign to man if the task requires his special capabilities.
Hazards	Tasks that are hazardous to man should be performed by machine only.

2.2.8.3 EVA Tasks, Rationale and Equipment. Skylab experience has shown the value of EVA to perform unscheduled maintenance, repair, and contingency tasks. The Skylab crew performed 82.5 man-hours of EVA during 10 EVA periods, although only 29 man-hours of EVA during 6 EVA periods had originally been planned. From the experiences of Skylab it is anticipated that there will be a great need for EVA activities on the Space Station especially in the early years.

EVA activity requires special equipment and procedures. These in turn will require accommodations in the basic Space Station design. A detailed list of the equipment and architectural design requirements for EVA activities are provided in Table 2-30. Table 2-31 is a detailed list of the ground rules for EVA activities.

Table 2-30. Equipment and Architecture Design Requirements to Support EVA Activities

1. Provide EVA crew translation and worksite stabilization in form of RMS and MMU
2. Payload designs will adhere to sharp edge, corner and protrusion criteria along translation paths and at worksites
3. Payloads will provide crew safety from electrical, fluid, radiation, mechanical and other hazards
4. OTV, TMS and satellites will be designed EVA compatible
5. Provide standardized interfaces with EVA tools
6. EVA crewman shall be supplied information and contingency operations instructions via a computer information system
7. EVA crew transfer corridors and work areas must be compatible with dimensions and mobility of EMU
8. Provide proper storage and maintenance areas for EMU items, spares and support equipment
9. Provide airlock and support equipment for two crewmen
10. Provide viewing port for IVA crewman to observe egress, ingress and EVA work activities
11. Provide handholds, translation rails, lights, and tether attachments to support egress, ingress, transfer and EVA work
12. Provide a hyperbaric chamber for decompression and detailed safety procedures (see Table 2-32)

Table 2-31. EVA Operational Ground Rules

- Use of a Space Station Extravehicular Mobility Unit provides:
  - -- No prebreathe
  - -- Non-venting/regenerative thermal control
  - -- Regenerative CO_2 control
  - -- 100 percent powered by rechargeable battery
  - -- EVA computer information system
  - -- On-orbit maintainability
- Each EVA crewmember has own EMU
- EVA by a single crewmember shall be permitted. However, an IVA crewmember shall be available at all times to engage in rescue operations
- One EVA per day per crewmember
- 8-hour EVA maximum per crewmember
- 12-hour EMU recharge period
- A minimum time factor margin of 25 percent shall be added to all computed tasks times to account for set-up, conversation, interruptions, and other hard-to-define delays
- Pre and Post EVA time allocations:

-- Suit docking	30 minutes
-- Airlock transition	25 minutes
-- Moving to/from worksite	5-15 minutes each
-- Suit doffing including suit cleaning and initiation of recharge	45 minutes

- EVA conducted in light and dark environments
- Helmet to provide head-up displays
- No assembly or EVA activities during flight vehicle approach and departure operations

There are both advantages and limitations to using the space suited crewman. The advantges are the human capabilities of:

a. Immediate visual feedback

b. Problem solving

c. Rapid response to emergencies

d. Trouble shooting

e. Providing contingency repair

The main limitations are his mobility, strength, stay-time, and physical comfort. The EVA activity also carries with it certain inherent safety risks. A summary of the hazards associated with EVA activity can be found in Table 2-32.

Table 2-32. Summary of Hazards During Extravehicular Activity

CONDITION	METHOD OF HAZARD REDUCTION	EMERGENCY PROCEDURE
Environmental		
Solar radiation	Use of visor and shielding afforded by structures	Wait for blindness to pass or wait for rescue
Particle radiation	Avoid regions of high flux density	Withdrawal to craft
Micrometeorite flux	Use of shielding afforded by structures	Return to craft
Vacuum	Suit maintenance and checkout	Use of emergency oxygen system and or crew rescue bag
Spacecraft discharge	Avoid attitude changes or jettisoning waste during EVA	Remove particles from face plate
Electrical potential	Provide electrical path among structures touched by astronaut. Danger from this source has not been determined.	(unknown)
Garment/Life Support		
Tears	Maintenance and checkout, short missions, avoid sharp objects, avoid narrow passages	Rescue if trapped, self-release to be avoided
Condensation on face plate	Short missions, frequent rest	Rest, wait for plate to clear, return to craft
Loss of communication	Check out communications frequently	Return to craft

Table 2-32. Summary of Hazards During Extravehicular Activity, Contd

CONDITION	METHOD OF HAZARD REDUCTION	EMERGENCY PROCEDURE
Crew Morphology/Health		
Vertigo	Avoid sudden movements, training	Rest or rescue
Rapture	Selection and training	Rest, communication
Dissociation	Training	Activity, communication
Fatigue	Training, frequent rest	Rest, return to craft
Fear	Training, communication bio-monitoring, return if fear increases with time	Perform familiar activity, return to craft, communicate
Bends	Denitrogenation procedure, slow change in pressure	Increase pressure, then reduce pressure slowly
Heat exhaustion	Monitor physiological variables, short missions, rest	Rest
Nausea	Selection and training, diet control, avoidance of fatigue	Reschedule EVA so man not required (return to craft at first symptom)
Operating Procedures		
Tangle umbilical	Training, monitoring of procedure by standby astronaut	Stop movement, allow standby to free lines
Caught between moving structures	Communications with other crewmen, training, improve design to avoid EVA near moving structures	Rescue

SOURCE: Air Force Systems Command Design Handbook 1-G (5) and Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

Due to the anticipation of unforeseen EVA tasks and the limitations of EVA activity, it is recommeneded that all hazards, repetitive and routine tasks be performed using remote operations, teleoperations or robotics. The following subsection discusses this in more detail.

2.2.8.4 Automated Tasks, Rationale, and Equipment. As discussed in Subsection 2.2.8.3, EVA has been successfully used in performing a wide variety of tasks. Even with this success, it is recommended that EVA be reserved for unscheduled, one time, and seldom performed tasks. Tasks that require short time periods of EVA with large intervals between occurrences or those repeated with each mission should be performed by remote operations, teleoperations, or robotics.

The development of teleoperator technology will provide many payoffs, a few of which are:

a. More effective utilization of EVA operations

b. Reduction in crew size

c. Extension of man's capabilities

d. Increase of operational safety

e. Increase in on-orbit servicing and assembly capabilities

The main payoff is the elimination of the problems and constraints of EVA. These include the limited visibility and movement of EVA crewmen, the inherent safety risks of EVA operations, and the length of an EVA.

The functions allocation analysis describes both the desired human and machine role in each function. The automated tasks identified in this analysis are both gross maneuvering and fine manipulative tasks. The gross maneuvering tasks include the capture and movement of large objects such as satellites, transportation vehicles, station modules, and construction materials. The fine manipulative tasks are those needed to replace the EVA crewman in inspection, maintenance, and assembly type functions. The capabilities of a fine manipulative device would include working latches and other fasteners, removing and replacing parts, and connection small cables.

The successful performance of these tasks do not rest solely on the maneuvering or manipulative device, but is shared by the design of the object to be handled or serviced. These objects should have modular servicing capabilities and contain universal components and built-in self test ability.

2.2.9 SPACE STATION CREW SIZE AND CREW CONSUMABLES ANALYSIS. The crew size includes the total number of crewmen needed to perform research, development and production, servicing operations, national security research and development, and Station operations. This crew size determines the requirements for crew consumables to be delivered to the Station by the Shuttle. This subsection presents the results of the analyses to determine these requirements.

2.2.9.1 Crew Size Requirements. To establish the crew size needed to accommodate the user requirements for research development and production, the number of manhours for the missions in a given year were totaled and divided into work shifts of 8 hours each. These requirements were average hours per day required to perform the tasks as defined at this time. The missions

requirements were not detailed enough to establish if these manned tasks were to be performed continually over the time given or if they were performed periodically over a 24-hour period. An example of a task performed periodically would be monitoring and adjustments for astrophysics, earth, environmental and atmospheric observations. The time needed to perform some of the tasks which occur at weekly or monthly intervals were converted to hours per day.

The equivalent man-years of crew time needed to perform the servicing missions was established using the timelines (shown in Figures 2-39 through 2-41) developed for nominal servicing activities along with the number of anticipated missions per year (see Table 2-33). This total time was then averaged over a 300-day year. This allows for a six-day work week plus a few extra days for unaccountable delays such as crew change over or illness. Days off for the crew will be staggered accordingly. Using the manhours needed per day, a crew size was established assuming an 8-hour work shift.

The times used for establishing the timelines for the nominal servicing activities reflect a 50 percent factor for delays and unforeseen activities. Wherever possible, the maximum time estimated to perform each functional task was used.

The crew requirements for the national security research and development is an estimate. This estimate is for 8 hours in the early years with an increase to 16 hours in the latter part of the decade.

The crew size for Station operations assumes the use of improved automation and control technology in later years, thus a reduction in manhours with increased missions. The activities considered for Station operation were described in paragraph 2.2.7.1.

Using the equivalent crew man-years established for each of the above activities, a crew man-years were calculated and are as shown in Figure 2-42. This crew size also reflects an 8-hour work shift per crew member and a 6-day work week. The work shifts will be adjusted to fit the user requirements and will also be varied to fit all contingency observations. The crew size is based on equivalent man-years and assumes that the crew members will be multidisciplined and cross-trained to perform several tasks.

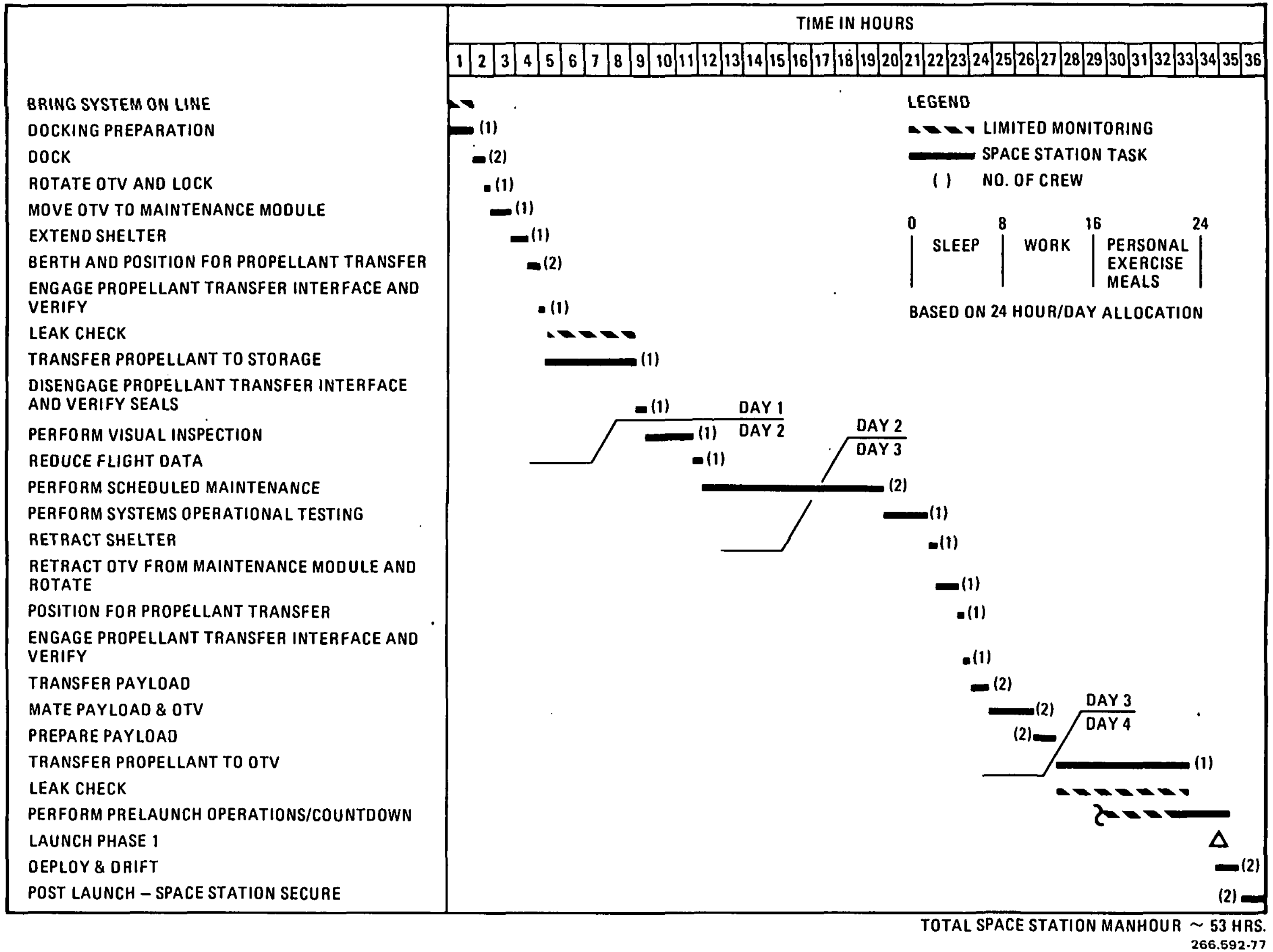


Figure 2-39. OTV Turnaround Timeline

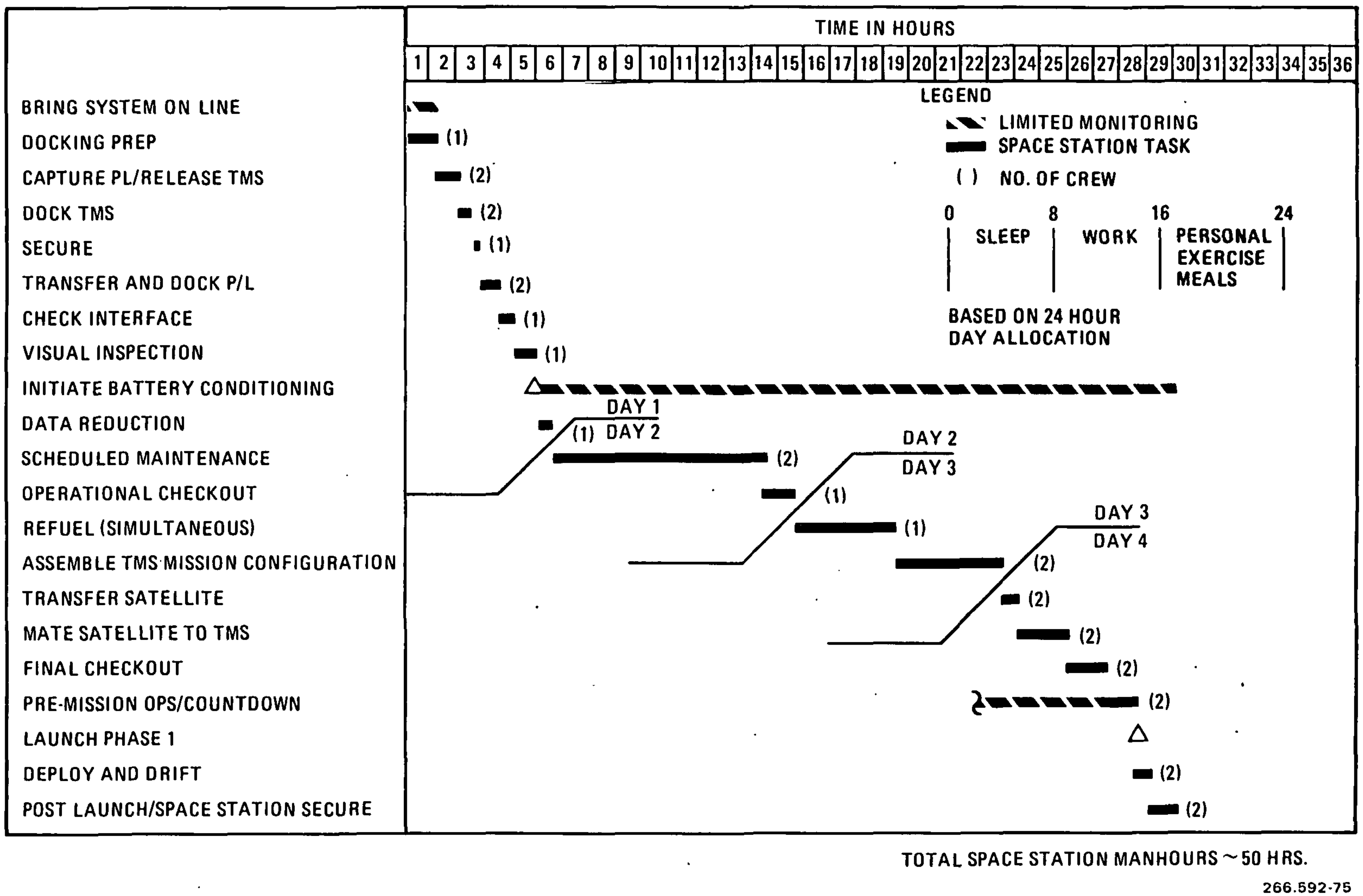
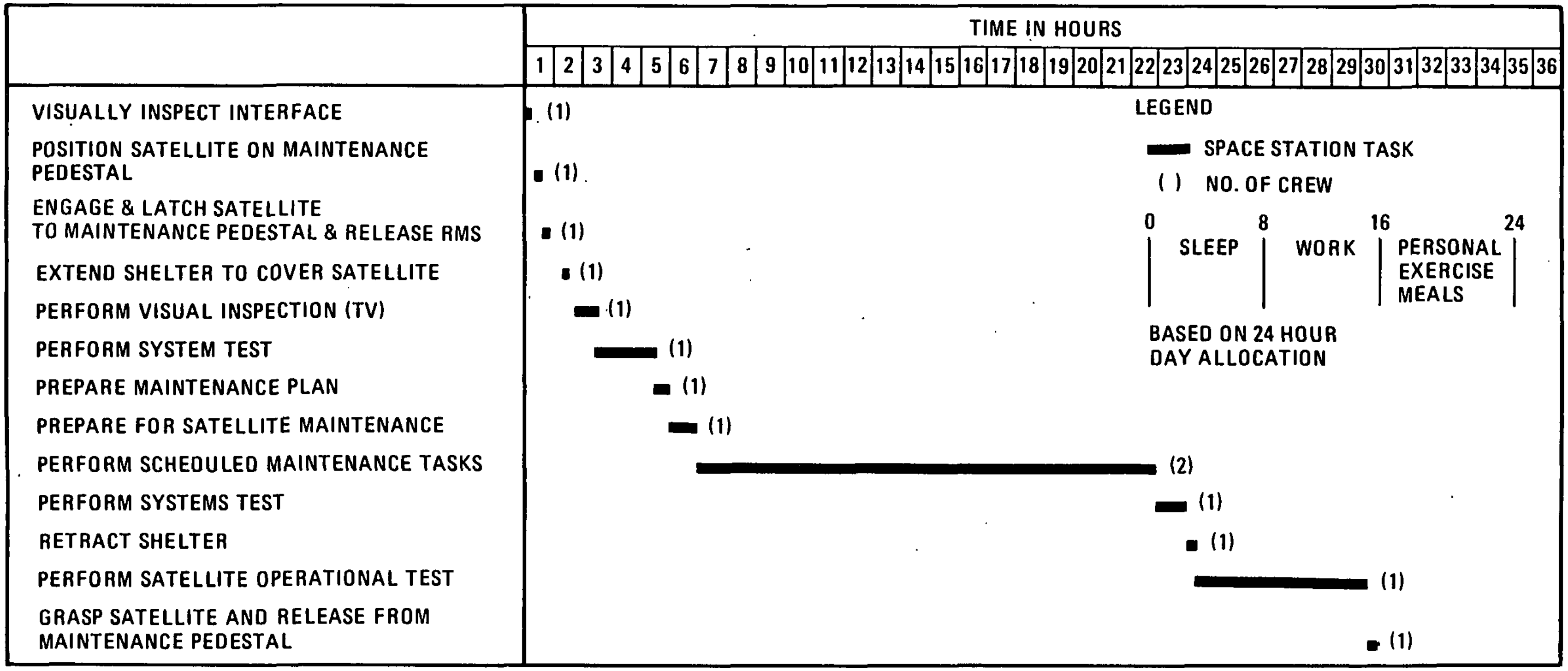


Figure 2-40. TMS Turnaround Timeline



NOTE: THE DOCKING AND BERTHING OF THE SATELLITE IS INCLUDED IN THE OTV & TMS TIMELINES.

TOTAL MANHOURS ~ 45 HOURS

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Figure 2-41. Satellite Servicing Timeline

Table 2-33. Manhour Requirements for Servicing Operations

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
OTV											
MISSIONS/YEAR					14	18	22	25	27	26	30
MANHOURS/MISSION					72	72	72	72	72	72	72
TOTAL MANHOURS/YEAR					1008	1296	1584	1800	1944	1872	2160
AVERAGE CREW TIME PER DAY					3.4	4.3	5.2	6.0	6.7	6.3	7.2
TMS											
MISSIONS/YEAR			12	12	15	17	18	19	20	20	22
MANHOURS/MISSION			75	75	75	75	75	75	75	75	75
TOTAL MANHOURS/YEAR			900	900	1125	1275	1350	1425	1500	1500	1650
AVERAGE CREW TIME PER DAY			3.0	3.0	3.75	4.3	4.5	4.75	5.0	5.0	5.0
SATELLITE SERVICING											
NUMBER OF ON STATION SERVICINGS			2	2	2	3	5	2	3	4	2
MANHOURS/MISSION			45	45	45	45	45	45	45	45	45
TOTAL MANHOURS/YEAR			90	90	90	135	225	90	135	180	90
AVERAGE CREW TIME PER DAY			0.3	0.3	0.3	0.45	0.75	0.35	0.45	0.6	0.3
TOTAL MANHOURS FOR SERVICING MISSIONS			990	990	2223	2706	3159	3315	3579	3552	3900
AVERAGE HOURS/DAY (APPROX. 300 WORK DAYS/YEAR)			3.3	3.3	7.4	9.0	10.5	11.0	11.9	11.8	13.0
AVERAGE CREW/DAY PER YEAR			0.4	0.4	0.9	1.1	1.3	1.4	1.5	1.5	1.6

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2.2.9.2 Crew Consumables Requirements. Based on the selected approach to crew and life support described in Subsection 3.2.6.4, an EC/LSS strategy was adopted as follows:

- Launch open-loop system
- Introduce new regenerative subsystems as experiments (technology demonstrations)
- Size the demonstration hardware such that it can become an operational unit after its flight verification (e.g., 2 man subsystems for water reclamation, carbon dioxide removal, etc.)
- Launch new subsystems with new modules
- Change out old open-loop subsystems as zero-G performance of regenerative subsystems becomes proven
- Retain 150 man-day open-loop emergency capability

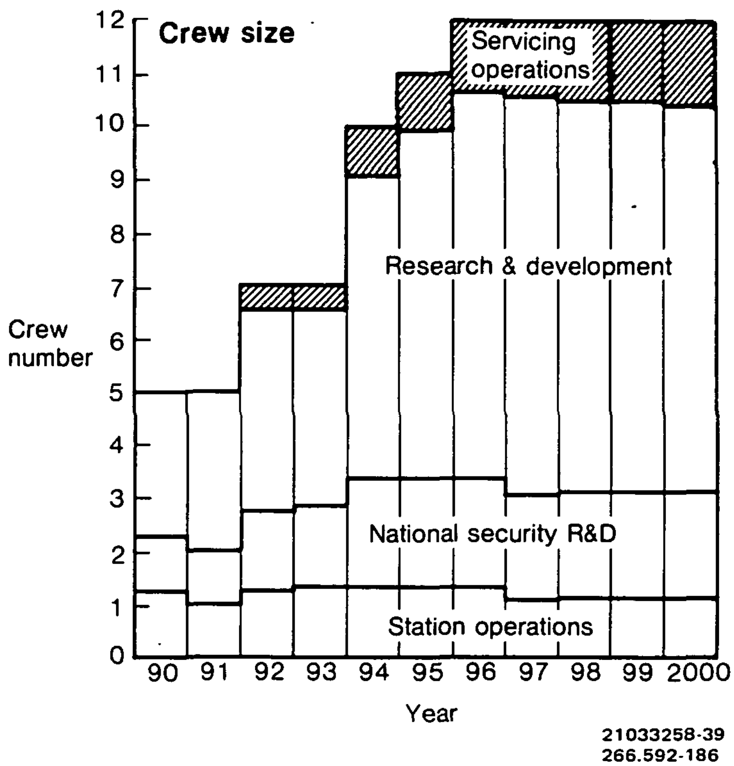

Figure 2-42. Space Station Crew Size Requirements

Using the crew size estimated in the preceding Subsection and the pressurized volume growth (Table 2-34) estimated for the Space Station architecture described in Section 4.0, and a crew consumables budget as summarized in Table 2-35, a total consumables requirement was determined for both an entirely open-loop EC/LSS (Table 2-36), and the selected partially closed-loop EC/LSS (Table 2-37). The total consumables required for each year are compared in Figure 2-43.

Table 2-34. Station Volume Growth

	YEAR										
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
HABITABLE VOLUME (M^3)	520	650	650	910	1150	1150	1360	1360	1360	1360	1360
PRESSURIZED VOLUME (M^3)	740	930	930	1300	1640	1640	1940	1940	1940	1940	1940
ATMOSPHERE LEAKAGE (Kg/DAY)	3.3	4.1	4.1	5.7	7.2	7.2	8.5	8.5	8.5	8.5	8.5

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Table 2-35. Crew Consumables Budget

	1990 – 1995	1996 – 2000	
WATER			
• DRINKING/FOOD PREP	8 (3.6)	8 (3.6)	LB (Kg)/MAN/DAY
• PERSONAL HYGIENE	12 (5.5)	24 (10.9)	LB (Kg)/MAN/DAY
• DISHWASH	50 (22.7)	100 (45.4)	LB (Kg)/DAY
• EVA COOLING	11 (5.0)	22 (10.0)	LB (Kg)/DAY
• CLOTHESWASH	0	28 (12.7)	LB (Kg)/MAN/DAY
OXYGEN (METABOLIC)	1.84 (0.83)	1.84 (0.83)	LB (Kg)/MAN/DAY
LiOH (FOR CO_2 REMOVAL)	6.8 (3.1)	6.8 (3.1)*	LB (Kg)/MAN/DAY
ATMOSPHERE RESUPPLY			
• LEAKAGE	7.3 (3.3)	18.7 (8.5)	LB (Kg)/DAY
• EVA AIRLOCK	2.2 (1.0)	4.4 (2.0)	LB (Kg)/DAY
FOOD	4.6 (2.1)	4.6 (2.1)	LB (Kg)/MAN/DAY
SUPPLIES & SPARES	821 (373)	693 (315)	LB (Kg)/MAN/90 DAYS

*FOR OPEN LOOP CALCULATION ONLY; RECOMMENDED PLAN REQUIRES NO LiOH EXCEPT FOR EVA

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2.2.10 OPERATIONAL FLOOR PLANS. A top level analysis of the functions required for performance of the mission set yielded four major areas of operational activities within the Space Station. These operational areas were defined to provide an early concept of operations floor plans which would allow the feasibility of on-orbit operations to be verified. These floor plans were developed to provide a guideline for future definition of the arrangement and location of facilities and missions on the Station.

2.2.10.1 Operational Areas. The four major operational areas are described as follows:

a. Crew Accommodation and Support areas provide functions which support the Station crew members. These functions, shown in Figure 2-44, were generally colocated for ease of access to work areas from the habitat area and quick access to the safe haven in the general purpose area.

   The Habitat and Logistics Areas are paired, with the Logistics Area serving as a pantry for the crew located in the Habitat. They are designated as separate areas in order to allow the Logistics Area to be a separate module in itself, which could be sealed off and detached, when empty, for return to Earth. The pantry concept eliminates the need for large storage volumes in the habitat, and for extensive transfer and stowage operations during every resupply cycle. In exchange for these benefits, the Logistics Module itself must be larger, since more access must be provided, thereby lowering the packaging efficiency. This is not as serious as it may seem: with the large volumes of water required in the open-loop years, the Logistics Module flights may come closer to being mass limited than would otherwise be the case.

Table 2-36. Open-Loop Resupply Requirements (kg/90 Days)

ITEM	YEAR	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	CREW SIZE	5	5	7	7	10	11	12	12	12	12	12
WATER		6,768	6,768	8,406	8,406	10,863	11,682	33,912	33,912	33,912	33,912	33,912
OXYGEN		374	374	523	523	747	822	896	896	896	896	896
LiOH		1,395	1,395	1,953	1,953	2,790	3,069	3,348	3,348	3,348	3,348	3,348
ATMOSPHERE		387	459	459	603	738	738	855	855	855	855	855
FOOD		945	945	1,323	1,323	1,890	2,079	2,268	2,268	2,268	2,268	2,268
SUPPLIES & SPARES		1,865	1,865	2,611	2,611	3,730	4,103	4,476	4,476	4,476	4,476	4,476
TOTAL RESUPPLY FOR 90 DAYS		11,734	11,806	15,275	15,419	20,758	22,493	45,755	45,755	45,755	45,755	45,755
TOTAL RESUPPLY FOR YEAR (Kg)		46,936	47,224	61,100	61,675	83,032	89,972	183,020	183,020	183,020	183,020	183,020

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Table 2-37. Partially Closed-Loop Resupply Requirements (kg/90 Days)

ITEM	YEAR	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	CREW SIZE	5	5	7	7	10	11	12	12	12	12	12
WATER		6,768	4,535	5,632	5,632	1,086	1,168	3,391	3,391	3,391	3,391	3,391
OXYGEN		374	374	523	374	597	0	0	0	0	0	0
LiOH		1,395	1,395	1,395	1,395	0	0	0	0	0	0	0
ATMOSPHERE		387	459	459	603	590	590	0	0	0	0	0
HYDRAZINE		0	0	0	0	651	651	3,848	3,848	3,848	3,848	3,848
FOOD		945	945	1,323	1,323	1,890	2,079	1,512	1,512	1,512	1,512	1,512
SUPPLIES & SPARES		1,865	1,865	2,611	2,611	3,730	4,103	3,780	3,780	3,780	3,780	3,780
TOTAL RESUPPLY FOR 90 DAYS		11,734	9,573	11,943	11,938	8,544	8,591	12,531	12,531	12,531	12,531	12,531
TOTAL RESUPPLY FOR YEAR (Kg)		46,936	38,292	47,772	47,752	34,176	34,364	50,124	50,124	50,124	50,124	50,124

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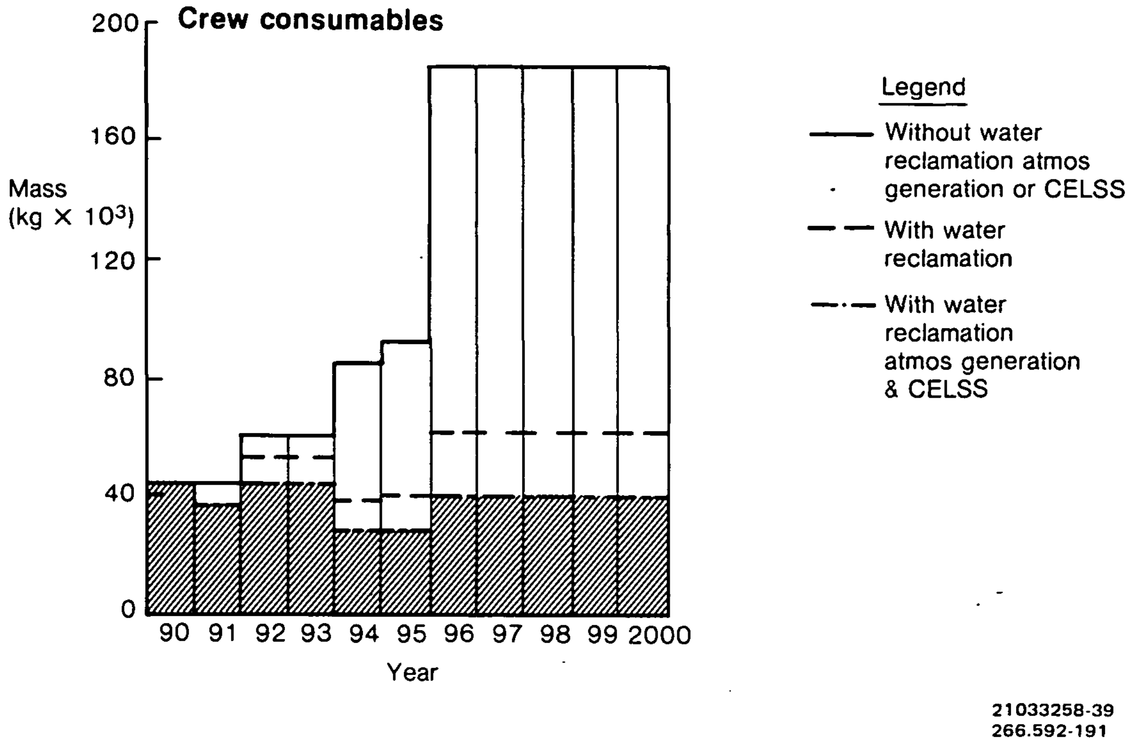

Figure 2-43. Space Station Crew Consumables Requirements

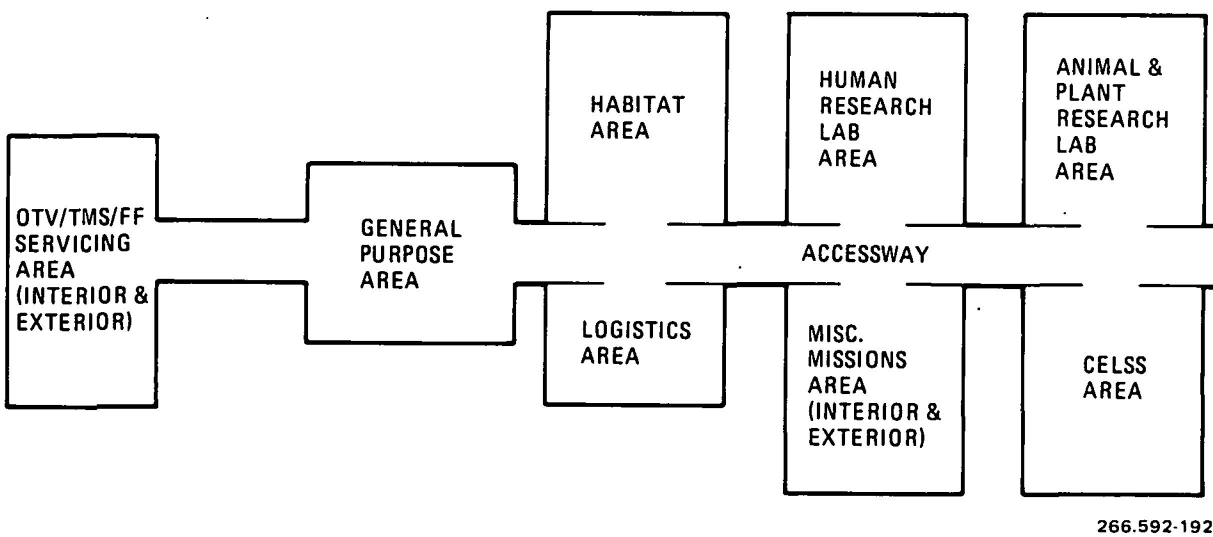

Figure 2-44. General Early Floor Plan for Crew Accommodation and Support

The Habitat Area (Figure 2-45) contains all of the functions for crew accommodation. It must be located near the Logistics Area for ease of access to food supplies, and must be located near the General Purpose Area since sleeping crew members will have relatively long reaction times if there is a need to reach the Safe Haven. The Habitat Area is also located apart from the Mission areas in order to provide a physical separation between work and leisure areas.

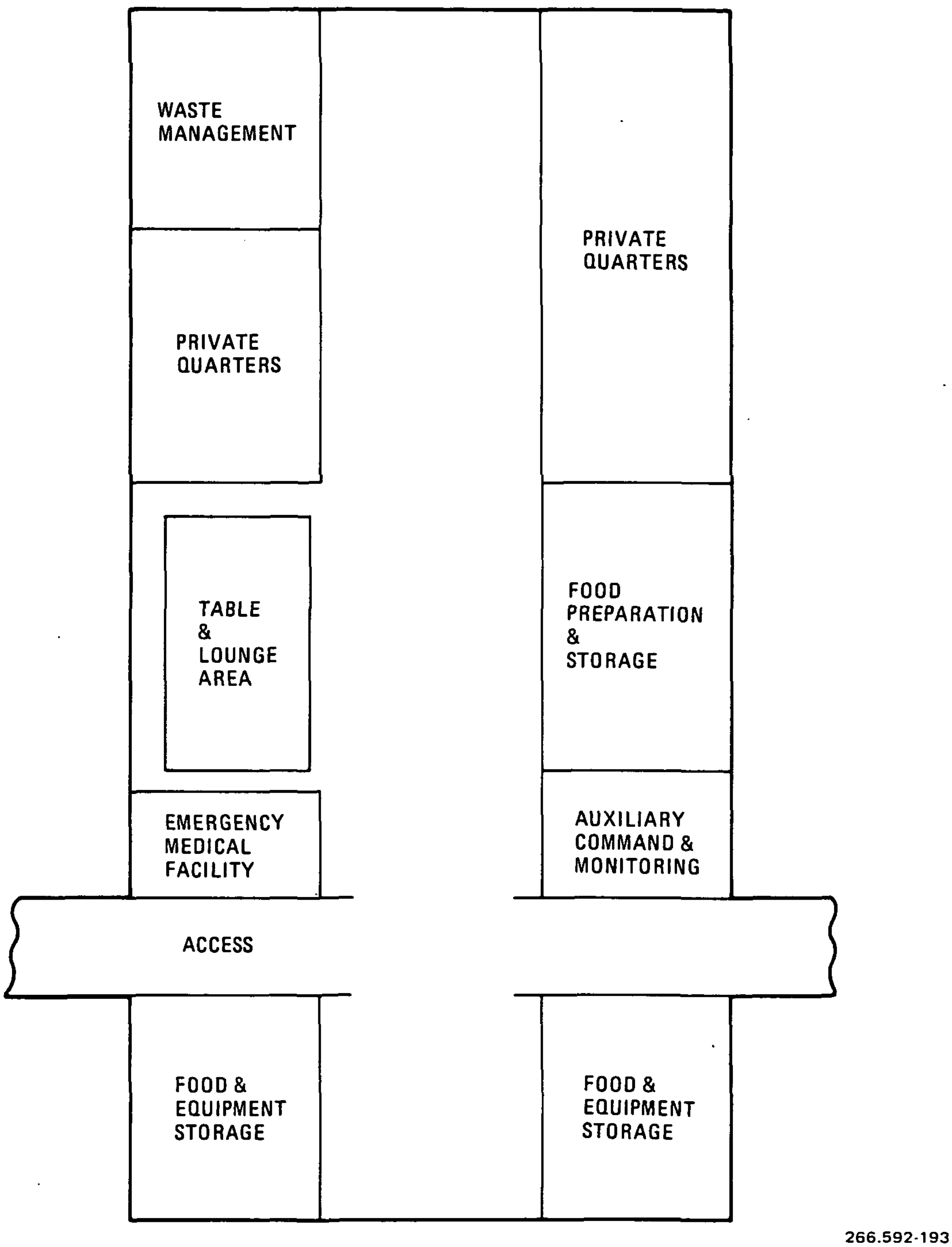

Figure 2-45. Habitat Area

b. Missions, Research, Development, and Production areas were conveniently divided into four categories. Three of these were composed of single missions large enough to require a major area to themselves. These include:

- Human Research Lab — GDCD 0300 — 112 m^3
- Animal & Plant Research Lab — GDCD 0301 — 76 m^3
- Dedicated CELSS Module — GDCD 0342 — 97 m^3

All three of these are listed in the data base as separate modules. The remaining missions can be accommodated in the single working area indicated for miscellaneous missions.

The Mission areas are located at the extreme opposite end of the Station from the propulsion and RCS on the General Purpose Module.

c. General Station Operations functions are those which serve as interfaces between crew and station or between the station and another vehicle. These functions generally lend themselves to the description of the Safe Haven concept, so they were combined in a single area to perform that function. These basic functions are combined with the other functions required for the Safe Haven, particularly medical facilities, waste management, food preparation and storage, command, control, communications, airlock, EVA preparation and suit refurbishment (Figure 2-46). Some level of sleeping or private quarters are also required. In sum, these requirements generally describe a self-sufficient vehicle, for which reason this area is also considered to be the initial core. Current estimates indicate that the total Safe Haven will require about 100 m^3 in dedicated habitable volume for the crew sizes from 1990 through about 1994. If a full size (120 m^3) module were used for a General Purpose Module which contains the Safe Haven, 20 m^3 would be available for expanded crew quarters or for missions equipment and storage. This condition would allow the General Purpose area to be used as an overflow accommodation for crew quarters and Missions performance/storage in the event that the available standard Habitat and Mission Modules do not contain sufficient volume. This is turn allows the delivery of a second Habitat to be delayed until 1994, and allows delay of the third until after 2000. The location of the command, control, and communication functions in the General Purpose Area allows the area to be used as the primary Command Center (bridge) until the full-up Center containing OTV and TMS functional control is delivered in 1994. After 1994 the General Purpose Area would also function as an Auxiliary Command.

In summary, the General Purpose Area contains the following functions: Safe Haven, Crew and Missions Overflow Accommodation, and Command.

The General Purpose Area also will include the propulsion and RCS hardware required by the Station between 1990 and 1994. For this reason, it must be located at one extremity of the Station during those years.

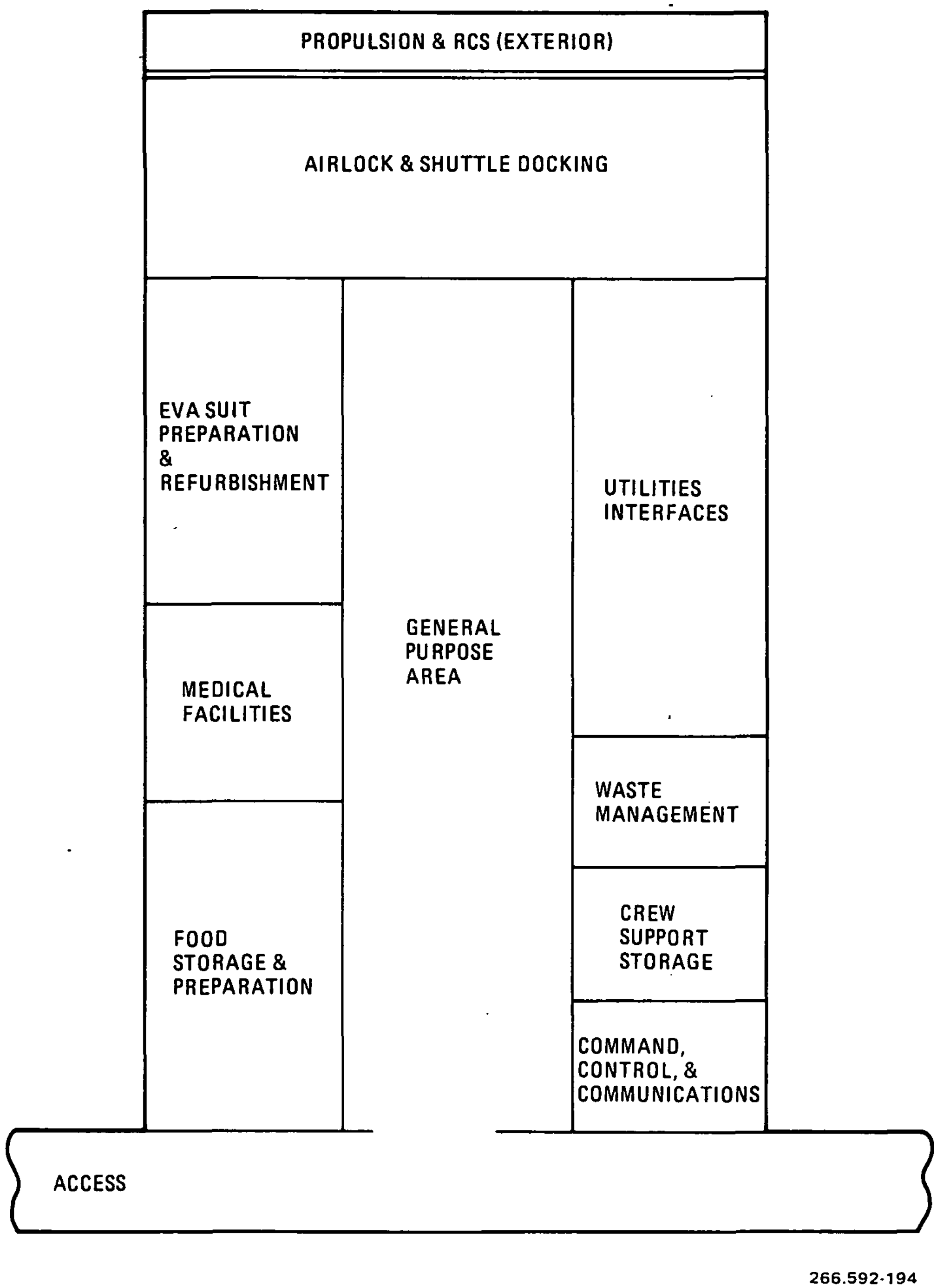

Figure 2-46. General Purpose Area/Safe Haven

d. The OTV/TMS/FF Servicing Area, shown in Figure 2-47 has been laid out in somewhat more detail in order to gain a better understanding of the elements required to accommodate these operations. The major elements of this area are interconnected through a combination strongback and pressurized passageway. The passageway allows ready manned access to all major elements and service areas.

A pressurized maintenance module is provided in the OTV service areas to permit the more intricate sections of the vehicle to be maintained when required in a shirtsleeve environment.

The handling and transfer of payloads, modules and Shuttle cargo as well as the berthing and docking of OTVs, TMSs and FFs is accommodated by Remote Manipulation Systems on each of the OTV maintenance shelters.

This floor plan concept generally allows most servicing and maintenance activities to be performed with minimum EVA.

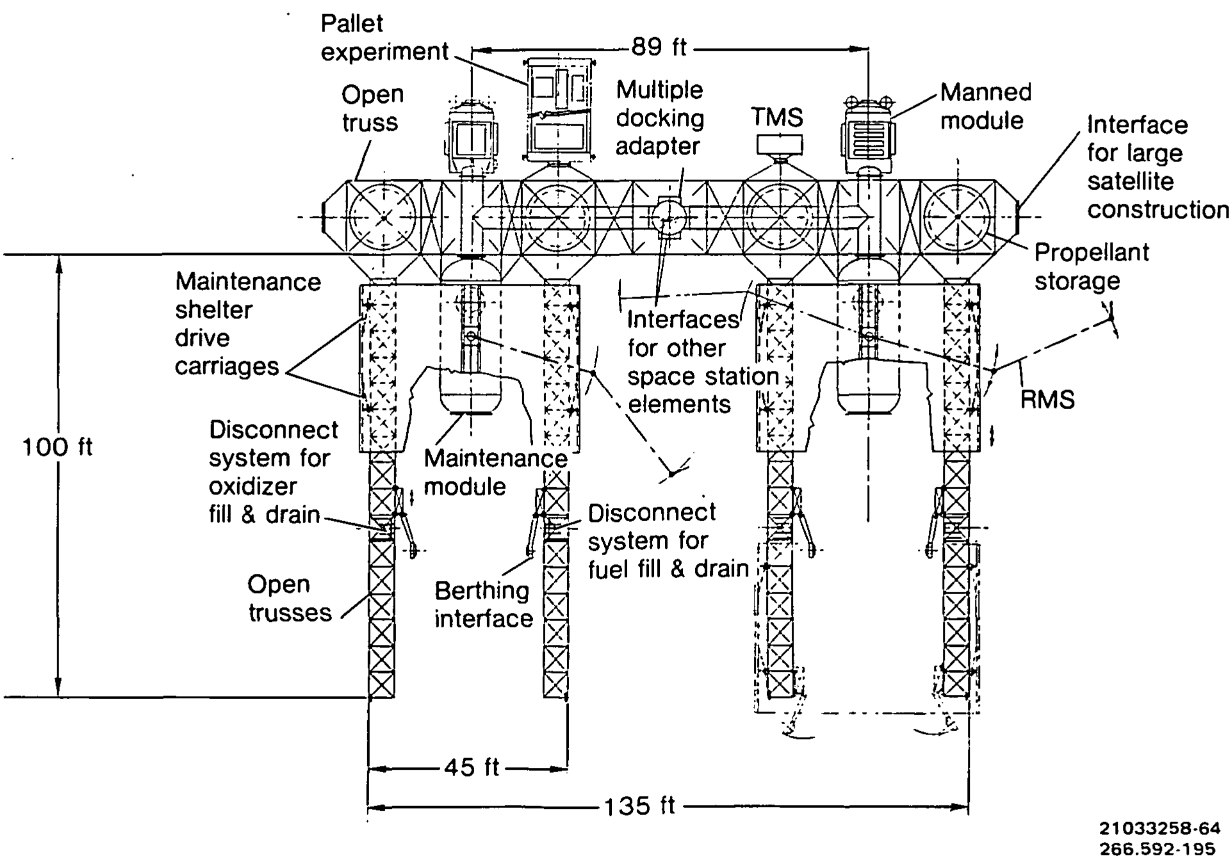

Figure 2-47. Space-Based OTV Servicing Facility Concept

SECTION 3

MISSIONS ACCOMMODATIONS ARCHITECTURAL AND EVOLUTIONARY OPTIONS AND TRADES

The Space Station System Architecture that will best satisfy the baseline missions set summarized in Subsection 2.1.1 of Book 2 has no unique solution. There are any number of architectural options for an overall space system that will accommodate the missions requirements. This section presents the space system options considered and the trade-offs performed in selecting a preferred architecture and program evolution. It also presents the results of Space Station subsystems options and trades and identifies implications for ground support operations and the Space Transportation System.

3.1 SYSTEM ARCHITECTURAL AND EVOLUTIONARY OPTIONS AND TRADES

The missions analysis presented in Volume II, Book 1 and summarized in Subsection 2.1.1 of Book 2 segregated the missions set into man-operated missions and free-flyer missions. The man-operated missions, that is, those requiring a manned presence to operate them, were listed by preferred orbits and acceptable orbits. Based on this information, various space facilities were identified that could accommodate some portion of the mission set. These facilities were then evaluated and tradeoffs performed to select a preferred baseline system architecture. The following subsections present the results of these options definitions and tradeoffs.

3.1.1 SYNTHESIS OF OPTIONS. Examination of the baseline mission set reveals the potential need for several different types of space facilities. These facilities break down into manned or unmanned as shown in Figure 3-1.

The unmanned facilities are divided into serviced or non-serviced types. The unmanned serviced facilities are either single missions free flyers or multimission platforms that are periodically serviced. Servicing may be performed by any of several means, including the Space Shuttle, a Teleoperator Maneuvering System (TMS), a manned sortie module, or by retrieval to a Space Station for manned servicing. Nonserviced facilities are conventional satellites that never receive servicing.

Man rated facilities of two types are possible. The first of these we refer to as a man supported facility. This type of facility would have the capability to support a small 2 to 4 man crew for several weeks. It would basically be Shuttle tended much the same as Skylab was Apollo tended. It would be used to conduct man-operated missions that required some extensive manned involvement, beyond the orbit stay time of the Shuttle, but which only required this attention for one time only or infrequent periods. The man-supported facility could be configured as a basic core of a Space Station such that at some future time it could evolve to a man-operated facility.

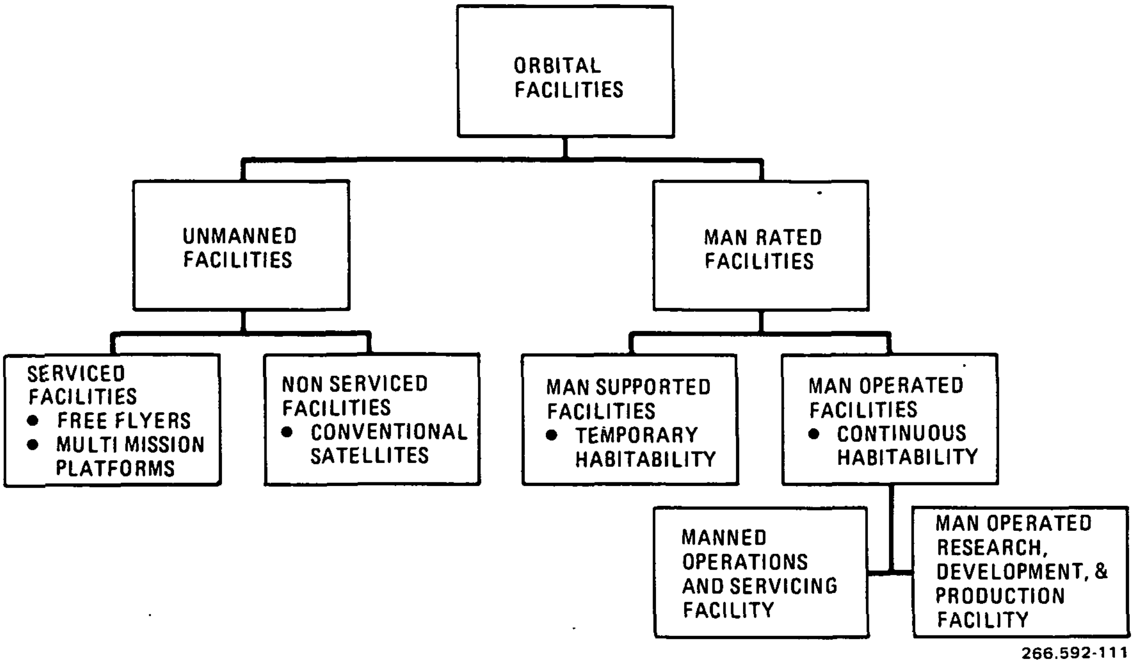

Figure 3-1. Missions Accommodation System

Man-operated facilities provide continuous habitability for operations crews and extensive accommodations for missions. These facilities may be separated into two types. The first type is a manned operations and servicing (O & S) facility, designed for the space basing of Orbital Transfer Vehicles (OTVs), TMS, and manned sortie modules. O & S facilities also have capabilities to service or modify free flyers and to construct large space systems as well as support technology development missions. The second type is a man-operated research, development, and production (RD&P) facility. As the name implies, this facility would provide the accommodations for numerous man-operated missions in the fields of Science and Applications, Commercial, and National Security R&D.

The criteria used to assign missions to each of these facilities is summarized in Figure 3-2. The figure also shows the orbits at which there is either a firm or potential need for each type of facility. From this matrix it is possible to describe a large number of overall space system architectural options. The basic question is, however, which of these facilities options can be justified on the basis of either high potential economic benefits and/or extent of mission needs.

3.1.2 <u>TRADE-OFF OF OPTIONS</u>. The missions set identified missions that could be performed on a man-operated RD&P facility at 28.5, 57 and 90-degree inclinations. The majority of man-operated missions could be accommodated at 28.5-degree inclination. A total of nine missions preferred 57 degrees, but of these nine, seven would accept 28.5 degrees and the remaining two would accept 90 degrees late in the decade. In effect, this eliminated further consideration of a manned Space Station at 57 degree inclination.

Facility Options	Mission Assignment Criteria	LEO Orbit Inclination			GEO
		28½ deg	57 deg	90-100 deg	
Man operated Research, development & production (RD&P)	• Benefits from man's presence • Compatible with man's presence • Acceptable orbit/inclination • Compatible with other missions	Yes	Yes	Yes	No
Manned operations & servicing (O&S)	• OTV/TMS base • Satellite servicing • LSS construction • Technology development	Yes	No	Yes	No
Man supported (temporarily manned)	• Needs occasional extended man's presence (>Shuttle) • Conflicts with other missions	Yes	No	Yes	No
Man serviced free-flyers and/or platforms	• Conflicts with other missions • Conflicts with man's presence • Needs other orbit • Needs infrequent service	Yes	Yes	Yes	Yes*
Nonserviced (conventional satellite)	• Short term • GEO satellite • Not serviceable	Yes	Yes	Yes	Yes*

*Part of missions set

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Figure 3-2. Space System Architectural Options Considered

The missions requiring 90 degrees are summarized in Table 3-1. This indicates that very limited missions requirements exist for a manned Space Station at 90 degrees late in the next decade. From this it was concluded that a 28.5-degree Space Station should be developed first.

The mission set supports the need for a man-operated RD&P facility at 28.5 degrees because of the potential long term economic and short term performance benefits this facility would provide. The mission set identifies a significant number of potential OTV and TMS missions that could be flown from a manned O & S facility at 28.5 degrees. The economic benefits along from a space based OTV capability as described in Volume II, Book 3, provide substantial justification for the O & S facility. The next question is, should the RD&P and the O & S facilities be combined or maintained as separate coorbiting facilities?

From a purely technical standpoint, the separate facilities approach has a great deal of appeal. The following is a list of the perceived advantages of separate coorbiting facilities:

a. The O & S facility could serve as a staging area for crew, supplies and missions that would be ferried to and from the RD&P facility via TMS or tether transfer systems. This would minimize the number of Shuttle visits to the RD&P facility.

Table 3-1. 90-Degree Orbit Missions Alternate Accommodations

- Eleven missions prefer polar orbit
  - Two missions are suitable as free-flyers
  - Four missions can accept a 28.5-deg orbit
- Summary of remaining polar orbit missions (1998-2000)

Type Facility	No. Missions	Description	Evaluation
RD&P	7*	• Earth exploration • Environmental observations	• Not compatible with 28.5-deg station • Manned interaction vital • Significant data/resource loss until 90-deg station provided
Operations & servicing	6 4	TMS missions/year OTV missions/year (DOD)	• If 90-deg station unavailable, shuttle launched & serviced missions more costly & mass limited

*Including 2 missions originally planned for 57-deg orbit

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b. The crew mix would be more specialized for each facility thus minimizing the need for multidiscipline training of crew members, e.g. OTV maintenance and operations specialists would not have to double as laboratory specialists.

c. Each facility would serve as an escape haven for the other. With manned sortie modules attached to each station, the crew could be quickly evacuated in the event of a catastrophe.

d. The dynamic disturbances and contamination environment attributable to the rendezvous and docking of OTV, TMS and Shuttle would be minimized for the RD&P facility.

e. Missions scheduling conflicts would be reduced because of fewer total missions accommodated on each facility.

f. The combined facility may become severely growth limited much sooner than anticipated.

g. The complexity of combining a greater number of subsystems and elements on one facility increases the operating risks.

In a brief study such as this, it is not possible to adequately address all of these issues. A greater understanding of the system configuration is required to fully evaluate the major concerns. However, an evaluation was performed to determine if the concerns d., e., f. and g. were significant enough to warrant recommending separate facilities.

Table 3-2 summarizes the results of the evaluation. The saving grace of environmental conflicts and scheduling conflicts was the relative infrequency of interfering OTV, TMS, FFS, and Shuttle-resupply missions. Growth limitations appeared to be manageable through the year 2000 based on the missions set. Greater complexity and risk could not be shown to be a decisive factor since it could not be quantified.

The issue of environmental conflicts was examined by determining which missions would be most likely to be affected. The MPS missions are sensitive to moderate dynamic disturbances such as docking and cargo handling. A number of astrophysics viewing missions would be sensitive to contamination and dynamic disturbances. In all cases, it was assumed that these missions would be shut down or otherwise isolated during the periods of disturbance and contamination.

Based on timelines developed for vehicle operations, the number of mission hours lost per event were estimated and the annual total mission hours lost computed. Figure 3-3 compares the cost of mission hours lost to the added cost of a separate O & S facility. It was concluded that neither technical nor economic justification could be developed to warrant a recommendation for separate RD&P and O&S facilities.

Man supported facilities (Figure 3-2) were considered as an option in the evolution of man operated facilities. A man supported facility at 28.5-degree inclination was considered as a possible early capability to support development of technology for OTV servicing. The facility would evolve into a manned O & S facility. Since a separate O & S facility was not selected, this option was also set aside.

Table 3-2. Combined Facilities Concerns

ISSUE	EVALUATION
• ENVIRONMENTAL CONFLICTS – DYNAMIC DISTURBANCES – CONTAMINATION	• INFREQUENT SHUTDOWN OF SENSITIVE MISSIONS REQUIRED
• SCHEDULING CONFLICTS	• MINIMIZED BY INFREQUENT O&S MISSIONS
• GROWTH LIMITATIONS	• GROWTH THROUGH 2000 MANAGEABLE
• GREATER COMPLEXITY & RISK	• NOT A DECISIVE FACTOR

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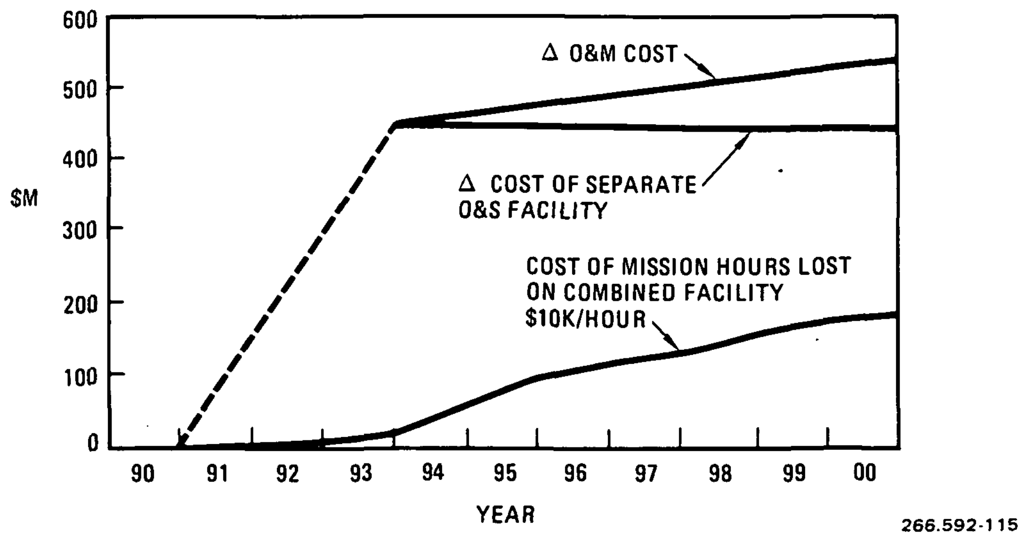


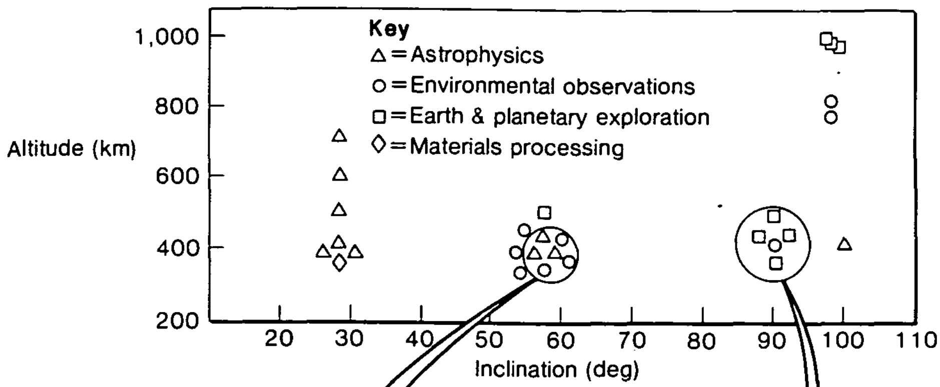
Figure 3-3. Cumulative Cost of Lost Mission Hours Versus Separate O&S Facility Cost

Man serviced free flyers identified in the missions set were examined as potential candidates for multimission unmanned platforms as shown in Figure 3-4. Of the free flyers at 28.5 degree inclination, only one was determined to be platform compatible. At 57-degree inclination, all but one of the free flyers was deemed platform compatible. Three were found to be short term (2 to 3 years) in the early part of the decade. However, six free flyers could all be placed on a platform in 1995 except one which could be emplaced in 1997. Based on the servicing and retrieval schedules given, all of these free flyers could be serviced by the Shuttle with one Shuttle flight per year.

Five platform compatible free flyers are found at 90-degree inclination, 400 km altitude. Three of the five could be emplaced with the platform in 1992 with the remainder to follow in 1994 and 1996. Again a single Shuttle flight per year to this platform would provide the needed servicing to these missions.

3.1.3 SELECTED BASELINE SYSTEM ARCHITECTURE. The selected baseline space system architecture and evolution is described in Figure 3-5. At the 28.5-degree inclination in LEO there is a single man operated RD&P facility starting in 1990 that continues to grow in capability through the year 2000. The TMS and satellite servicing capability are added in 1992 replacing the need for Shuttle free flyer servicing (FFS) missions at 28.5-degree inclination.

Programmatic analysis (Volume II, Book 3) shows the OTV operations and servicing capability could be developed and a single OTV placed in operation in 1994. The traffic model for OTV (Subsection 2.1.3) suggests the need for a second OTV in 1996. A cryogenic propellant delivery system would also be in place by 1994 to support OTV missions.



• 57-deg/400 km platform

Missions		95	96	97	98	99	00
Solar terrestrial obs	○	E	R				
Upper atmos research	○	E		S		R	
VLBI	△	E	S	S	R		
Adv solar obs	△	E		S		R	
Meteorology instr	○	E		S		R	
High-energy isotope	△			E	S	S	S
Platform		E	S/C	S/C	S/C	S/C	S

• 90 deg/400 km platform

Missions		92	93	94	95	96	97	98	99	00
Oper land systems	□	E		S/C		S/C		S/C		S/C
Geoscience-Geology	□	E	C	C	C	C	R			
FIREX	□	E			S			R		
Ocean instr P/L	○			E		S			R/E	
Renewable resources	□					E	S/C	S/C	S/C	S/C
Platform		E	S/C	S/C	S/C	S/C	S/C	S/C	S/C	S/C

E=Emplace R = Retrieval
S=Service C = Change configuration

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Figure 3-4. Additional Platforms for Leo Free-Flyers

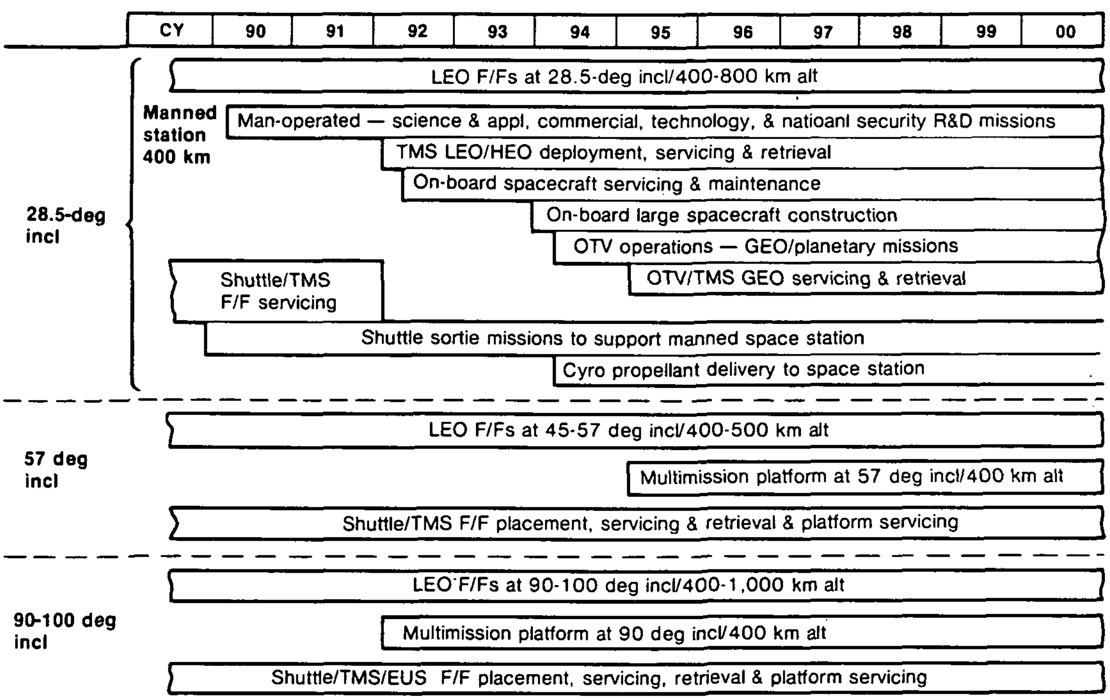

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Figure 3-5. Baseline Space System Architecture and Evolution Concept

At the higher inclinations, 57 to 100-degree LEO free flyers would continue to be emplaced, serviced, or retrieved by the Shuttle and TMS. A multimission platform would be emplaced at 90-degree inclination/400 km altitude in 1992. A second platform would be emplaced at 57 degrees/400 km in 1995.

Potentially, a second man operated facility could be emplaced at 90-degree inclination by the year 2000. The IOC of a polar station will depend on how substantial the need becomes late in the decade.

3.2 SUBSYSTEMS ARCHITECTURAL AND EVOLUTIONARY OPTIONS, TRADES, AND TECHNOLOGY NEEDS

The establishment of a viable architecture for a manned Space Station must include considerations of the major subsystems. In this section, the basic subsystems of a manned Space Station are addressed with respect to the issues and requirements which drive their architectures and technologies.

In some cases, such as the power management subsystem, the missions requirements have a major impact on architectural and technology approaches that can be considered. In other cases, such as flight and structure control, a better understanding of the Space Station hardware configuration is required before alternative controls subsystems approaches can be evaluated. Because of the lack of specific configurations, general approaches to subsystem architecture and technology requirements have been suggested which will require further scrutiny as the overall system becomes more well defined.

3.2.1 POWER MANAGEMENT. The Space Station architectural studies indicate that users will require deployment of a power system whose output to the users and station ranges from 40 kw (1990 IOC) to a final requirement of 220 kw (1996). Figure 3-6 shows the incremental growth expected. The increase in power requirements later in the decade occurs for two reasons:

a. The expectation that Materials Processes Science (MPS) will mature, and a significant user need for the added power will result.

b. The expectation that toward the end of the decade, closed loop life support systems (CELSS) will be used to support the Station to minimize the cost of resupplying crew consumables.

Should these events fail to occur, the requirements will be reduced. On the other hand, should MPS users needs develop more rapidly, even more power would be required. In addition to supplying the power required, the Station power system should also provide energy without a significant adverse constraint on other spacecraft systems. The system should also be affordable and compatible with mission orbital dynamics.

3.2.1.1 Power Generation Options. Two sources of energy are viable candidates to use to generate the energy - photovoltaic and nuclear. If a photovoltaic source is used, an energy storage subsystem is also required to provide power to the users during eclipse. This photovoltaic/energy storage

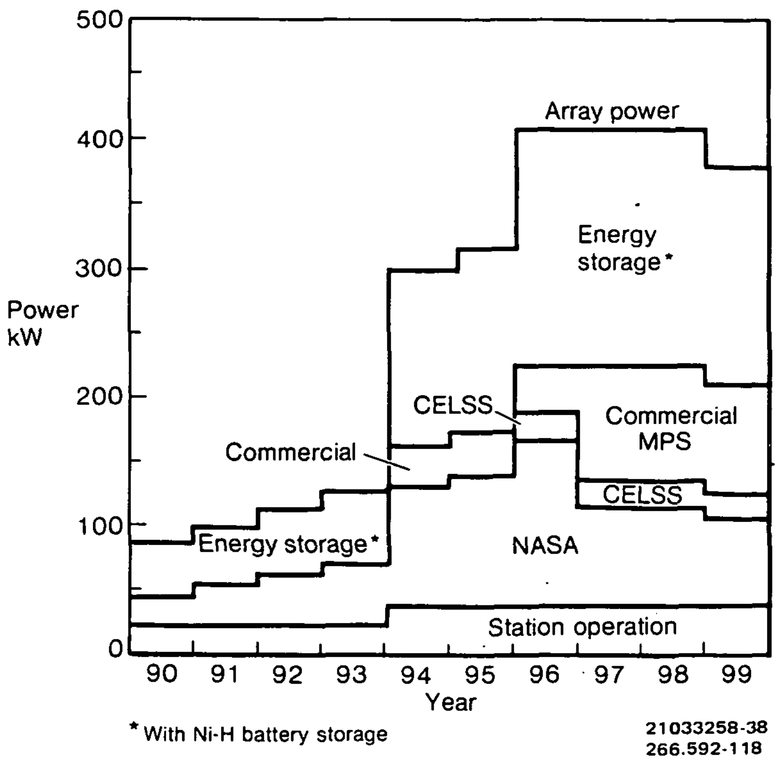

Figure 3-6. 28.5-Degree Space Station Power Requirement

approach can relatively easily be modularized, so that the following conditions exist:

a. Incremental growth is achieved by adding modules when the need arises

b. Reliability is enhanced by the ability to substitute working modules for failed modules.

The nuclear option, on the other hand, requires the addition of relatively large modules (100 kWe) at a time, assuming the SP-100 technology now under development by Los Alamos, or derivatives of it are used.

3.2.1.1.1 Semiparabolic Low Aperture Trough Solar (SLATS) Concentrator. The General Dynamics concept for the photovoltaic generation uses the SLATS concentrator approach (first described by us on contract NAS3-21951). Figure 3-7 shows the approach. Aluminum semiparabolic troughs focus energy on the General Dynamics patented dual bandgap (U. S. Patent 4328389) receiver. The receiver uses both gallium arsenide and silicon cells to over 20 percent efficiency (18 percent net, 220W/m^2 when mirror and spacing losses are included).

The SLATS concept is a part of our architecture because its efficiency reduces Station drag, and its broad roll axis pointing tolerance make it well suited for long, narrow array wing modules. The concentration will also reduce generation costs significantly.

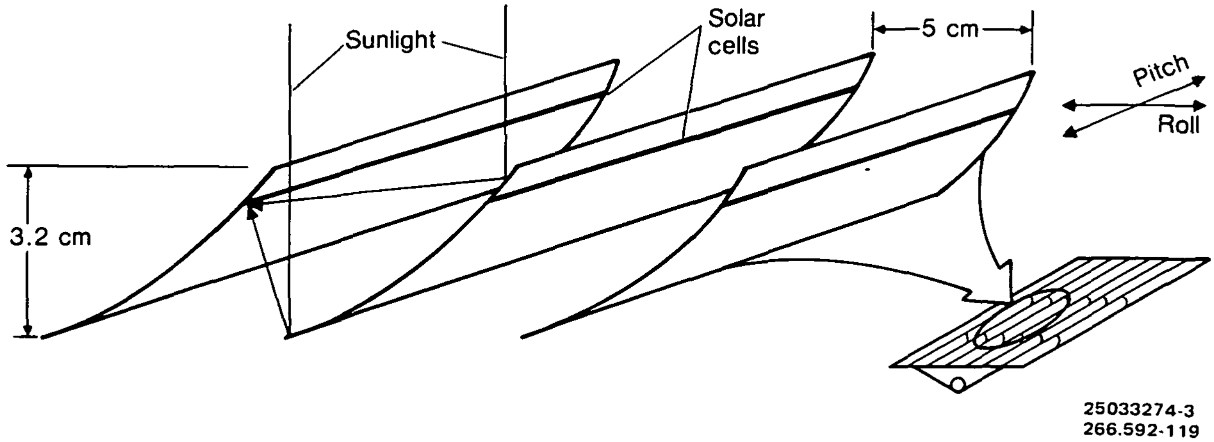

Figure 3-7. Semiparabolic Low Aperture Trough Solar Concentrator

3.2.1.2 Solar Array Pointing Constraints and Interactions. For the 28.5-degree inclination Space Station, the solar pointed photovoltaic arrays must be compatible with solar declinations which range from 5 to 52 degrees. Further mission studies indicate the desirability of using both local vertical and inertial orientations, the former call for either two gimbal array design or significant station roll control. Phase 2 architectural studies indicate missions which require earth pointing (local vertical attitude), hence a second roll gimbal is a recommended part of our architecture.

As the array grows modularly to meet its ultimate output requirements (400-600 kW), the modular array wings will be subject to translational as well as rotational disturbance inputs. Some of the inputs are self-induced - both pitch and roll rotations induce bending motions. Since the gimbaling is somewhat discontinuous due to bearing striction, approaches must be adopted to avoid coupling the striction induced disturbance frequency with the array first or second bending mode frequencies. These can include:

a. Active vibration suppression

b. Use of higher array wing natural frequencies

c. More complex gimbaling control

Without these precautions, penalties would be imposed on the spacecraft control system to handle complex array motions caused by the very lightly damped, high "Q" oscillations of multiple wing modules. The SLATS design, with its stiff truss backbone and fewer wings can meet these needs well. Because the SLATS design is more efficient, fewer wings are needed for a given power requirement.

3.2.1.2.1 Drag penalties. In LEO, a photovoltaic array, due to its relatively large area, imposes atmospheric drag on the spacecraft. Since

area decreases with increased array efficiency, drag penalties can be minimized by an array with greater efficiency. These penalties include:

a. Velocity makeup

b. Large disturbance torques for the attitude control system

In addition to minimizing array area, drag can also be minimized by feathering. If loads are off, or if the eclipse period is shorter (as it is when 53-degree declination is reached and it is summer or winter), feathering the array so it is not broadside to the orbital velocity vector reduces its drag and associated drag penalty. The efficient SLATS design will then minimize station drag. Just the reduction in area alone would allow the Station to be 15 nm lower in altitude (all other things being equal). The equivalent cryogenic propellant saving for the Orbiter/external tank would be an extra 2500 pounds (4 percent more payload) per flight.

3.2.1.2.2 Time-phase construction of the solar array using array wing modules. Station baseline architecture defines array power requirements which are most cost-efficient. If about 50 kWe is initially deployed in 1990, and then later (mid-1990s) added to modularly bring the full capability up to 500 kWe.

This incremental growth approach allows for technology improvements to be phased into the later deployed wings, to save on cost, mass (Shuttle payload) and consumables (drag makeup).

3.2.1.2.3 SLATS solar array costs. The mirrors for the SLATS concentrator can be extruded from aluminum at costs of about $1/watt. Front and back mirror surfaces can be provided for similar pricing. Thus, the major costs involve the concentrating solar cells and their interconnection.

The fact that photovoltaic cell area is reduced by the concentration ratio of the SLATS concentration means that much less (at least an order of magnitude reduction) will be seen in the amount of purified semiconductor material for the cells. Even though the cell grid line structure is more complex, total life cycle cost should be greatly reduced.

The SLATS design features cells whose basic dimensions are close to those of large integrated circuits. This means that the IC automatic bonding machining approach can be used to interconnect cells to collection flexible circuits, with all bonds verified as well. Thus, just as it has been for commercial integrated circuits, the use of automatic interconnection will allow interconnection costs to be reduced as well.

3.2.1.3 Nuclear Interactions and Penalties. If 100 kWe nuclear reactors are used to supply the incremental power required, two reactor modules plus the initial photovoltaic system could support Station user needs. The penalties which must be addressed for the nuclear systems approach include:

a. Safety of system design in orbit should the reactor accidentally reenter the Earth's atmosphere or melt down.

b. Lack of Prior to Launch testability.

c. Radiation interactions for the Station crew, and other station equipment especially in the event of an accident.

d. The nuclear technology will have significantly higher risk - because it is new, uses significantly higher temperatures, is harder to test, and more difficult to analyze the test results.

e. High cost (up to as high as $1000/watt).

These safety, risk and cost concerns make the nuclear option less attractive.

3.2.1.4 Energy Storage. Even if a nuclear reactor is utilized to provide some Station power in the late 1990s, the power source deployed initially will be photovoltaic. In the selected 28.5-degree orbit, an energy storage system will be needed to provide power during eclipse. The system should:

a. Provide incremental energy growth with time - as required by the users - up to the full 250 kWe need if a nuclear system is not used.

b. Provide energy at a reasonable cost and for as low a mass penalty as can be achieved with available technology.

c. Be safe, reliable, and have a long enough life for reasonable life cycle costs.

d. Take advantage of the operational approach (Shuttle serviced) if this could lead to cost savings.

e. Use Array Peak Power - if this is advantageous.

f. Be able to supply high peak powers for short times.

3.2.1.4.1 Alternative technologies considered for the study. Because of study scope, the study evaluated only two of the potential energy storage options. They were: Nickel Hydrogen batteries and Fuel Cell/Electrolysis systems. Other feasible options - such as flywheels or High Energy Density Batteries (NaS, etc.) were not evaluated, although it is recognized that with development they could become technology ready by the mid-1990s. Table 3-3 lists some of the expected performance parameters of the two candidates, and penalties associated with the inefficiencies of fuel cells compared to nickel hydrogen.

Table 3-4 summarizes our conclusions concerning the two alternatives. Initially, a Fuel Cell/Electrolysis system would weigh more. The extra weight results from two factors:

a. The system is somewhat more complex, with the fuel cell separate from the electrolysis unit.

b. The fuel cell is less efficient than the battery; because of the inefficiency, there is a solar array penalty (extra solar array mass and area required to generate the extra power) and a radiator penalty to reject the additional thermal load. The table shows the penalty is significant even if the efficient SLATS approach is used.

Table 3-3. Five Year Comparison of Energy Storage Options for a 25 kWe Module

	Option			
		NiH BATTERIES		Fuel Cells/ Electrolysis
Storage Device Operating				
Per Module Required Load Power		25 kW		25 kW
Power Distribution Losses	(η=.97) +	0.8 kW	(η=.97) +	0.8 kW
System Power Required		25.8 kW		25.8 kW
Required Storage Energy for 34 min of Shade		14.7 kWh		14.7 kWh
Storage Device Losses	(η=.95) +	0.7 kWh	(η=.55) +	12.0 kWh
Required Energy from Storage		15.4 kWh		26.7 kWh
Storage Device Charging				
Required Replenishment Energy		15.4 kWh		26.7 kWh
Charging/Electrolysis Losses	(η=.87) +	2.3 kWh	(η=.90) +	3.0 kWh
Total Replenishment Energy		17.7 kWh		29.7 kWh
Power Required for 56 min. of Charging		19 kW		31.9 kW
Power Distribution & Rectification Losses	(η=.95) +	1.0 kW	(η=.95) +	1.7 kW
Total Power Required by the Array to Maintain Storage Devices		20 kW		33.6 kW
Effect of Storage Device on System Mass				
Specific Energy Rating		25 $\frac{\text{W-hr}}{\text{kg}}$		30 $\frac{\text{W-hr}}{\text{kg}}$
Mass for Energy Storage		800 kg		928 kg
Mass Including Array at 50 W/kg		1700 kg		2150 kg

3.2.1.4.2 Energy storage location and its waste heat rejection constraints. With the photovoltaic option, the energy storage system must also be configured so that it does not impose undue penalties on other spacecraft systems. The important issues are:

a. Crew and Station Safety (crew shielded from accidental explosion).

Table 3-4. Energy Storage Issues

	TECHNOLOGY	
ISSUES	NICKEL HYDROGEN	FUEL CELL ELECTROLYSIS
Ability to Support Mission (Technology Readiness at the Stated Performance)	Available at about 25 W-hr/kg	Modest development required to achieve 30 W-hr/kg
Safety & Reliability	Reliable if properly modularized - safety shield desirable	Reliable if properly modularized - safety shield desirable
Shuttle Service Benefit/Modular Add-On	Δ modules only	Can be used to make up for any leaks + modules
Array Peak Power Usage	Not too probable - peak currents would be less than desirable	Probably - requires some test data to ensure no significant life degradation results
Array and Radiator Penalties	Acceptable	Significant - Increased efficiency needed - but SLATS could help
Cost	Acceptable	Inefficiency also 's cost

b. Waste Heat Rejection - location in proximity to waste heat radiators themselves should be avoided.

Both of these issues suggest that energy storage batteries should be located either on the array or on the array support boom.

3.2.1.4.3 Energy storage system cost. The cost of the energy storage options can be estimated using data previously obtained (Contract NAS3-21951). The Solar Array cost deltas associated with fuel cell inefficiencies are based on updated estimates for SLATS concentrator for both monolythic multiband gap cells and the General Dynamics dual-band gap receiver. These indicate that the penalties associated with added array for the fuel cell/electrolysis unit will make it more expensive than the Nickel Hydrogen option.

3.2.1.5 Power Distribution. The Station will require a Power Distribution system which works like a utility distribution system, i.e., it must be versatile, reconfigurable (as load modules are added and subtracted), and capable of handling the growth in power needed.

There are two major choices when considering power processing hardware for power management system design. The first is a conventional approach which uses a dc regulation and distribution system. The users are required to connect their loads to a high voltage (100-200 vdc) interface. The supporting logic for this choice usually states that this approach minimizes the amount of power processing equipment required. This is only true if you connect the power processing line at the bus connector. Although this approach looks good in the power system budget, it simply shifts a major portion of the power processing burden to the user. The total amount of power processing equipment which must be delivered to and installed on the space station can grow significantly.

The second and preferred choice is an integrated ac system approach which looks like a utility power system and is exceptionally "user-friendly". A diagram of our approach to such a system is shown in Figure 3-8.

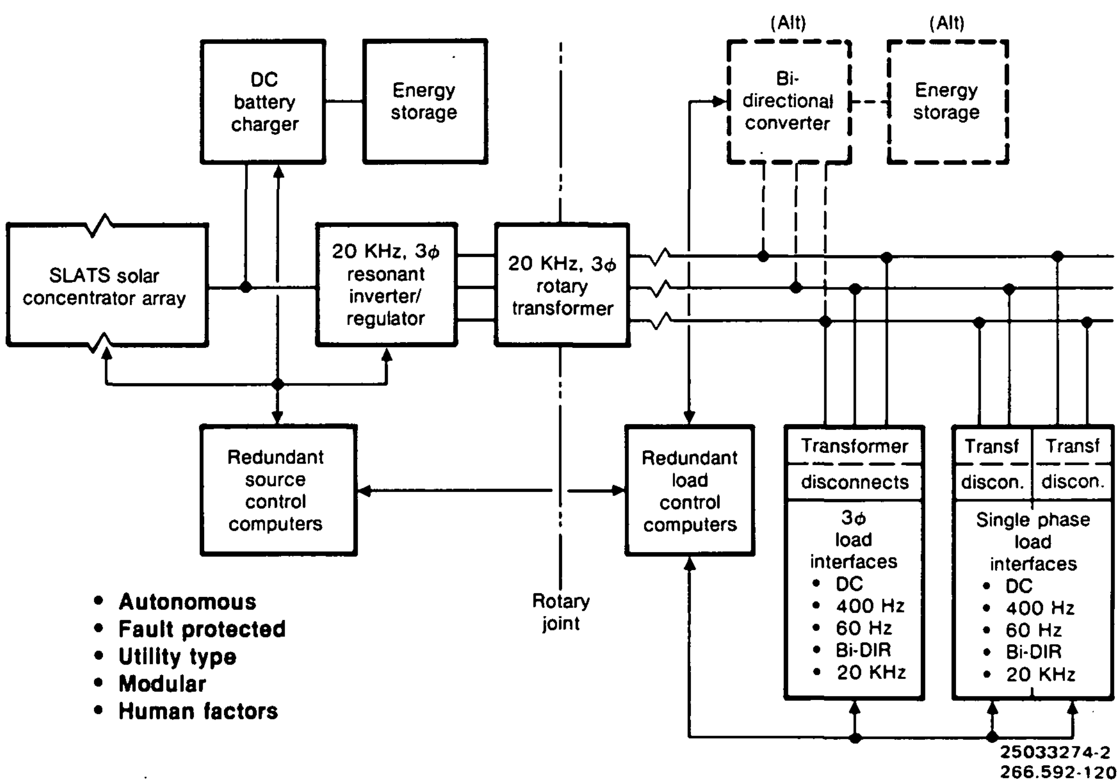

Figure 3-8. Space Station Power System

The system includes a regulated high-voltage three-phase ac distribution bus operating at 20 kHz. The dc to ac inversion is accomplished at efficiencies greater than 97 percent using a series resonant technique. All sliding-contact interfaces (slip-rings, user disconnects, etc.) are replaced by special-designed transformers. Transformers supply easy voltage level changes and solar array and load requirements are independent of the transmission voltage. The design has a family of user interface modules which meet a wide range of user requirements (as shown in Figure 3-8) making the system truly user-friendly.

Our detailed studies have shown (see NASA CR-159834) that such a system will actually cost less and have lower weight and volume than an equivalent dc system, if all the power processing equipment (including that on the user side of the interface) is included.

3.2.2 THERMAL MANAGEMENT. The Space Station thermal management system must support the demands of a wide range of users including the Space Station subsystems and the various payloads. The need to support a broad range of activities, many of which are currently not well defined, implies that a highly versatile heat collection, transport and rejection system is required.

In past and current space systems (Shuttle and Spacelab technology), passive thermal control or the use of pumped liquids and electrical heaters has satisfied thermal management requirements. The pumped liquid system has required careful ordering of components in the heat transport loop, however, to provide designed temperature control capability. For the evolving Space Station with its modular and growth characteristics, the thermal management system must have exceptional capability.

3.2.2.1 Requirements and Issues. Based on our mission requirements studies, three major functions have been identified for the Space Station. These are 1) the man-operated facility which provides for long term man-operated missions in space, 2) the Orbital Transfer Vehicle (OTV) base for placement of spacecraft in GEO or on planetary missions, and 3) the man-tended free-flyer function which provides for the servicing and maintaining of free-flying spacecraft as required. All of these functions require the management of thermal energy. The early man-operated facility in LEO at 28.5-degree inclination will grow to accommodate a wide array of research, development and production activities. These will have the largest thermal management requirements. Other portions of the overall Space Station assembly which subsequently become operational will have smaller thermal management requirements.

As a result of our mission analysis studies, we anticipate that the initial Man Operated Research, Development and Production facility (1990 to 1993) payload waste heat rejection requirements will be on the order of 25 to 60 kW with intermediate requirements of about 160 kW (1994 to 1995) and ultimately about 225 kW for the 1996 to 2000 time period as shown in Figure 3-9. To minimize initial cost, the thermal management system will be initially configured for the 25 to 60 kW capacity, and have the capability for growth to at least 250 kW or more.

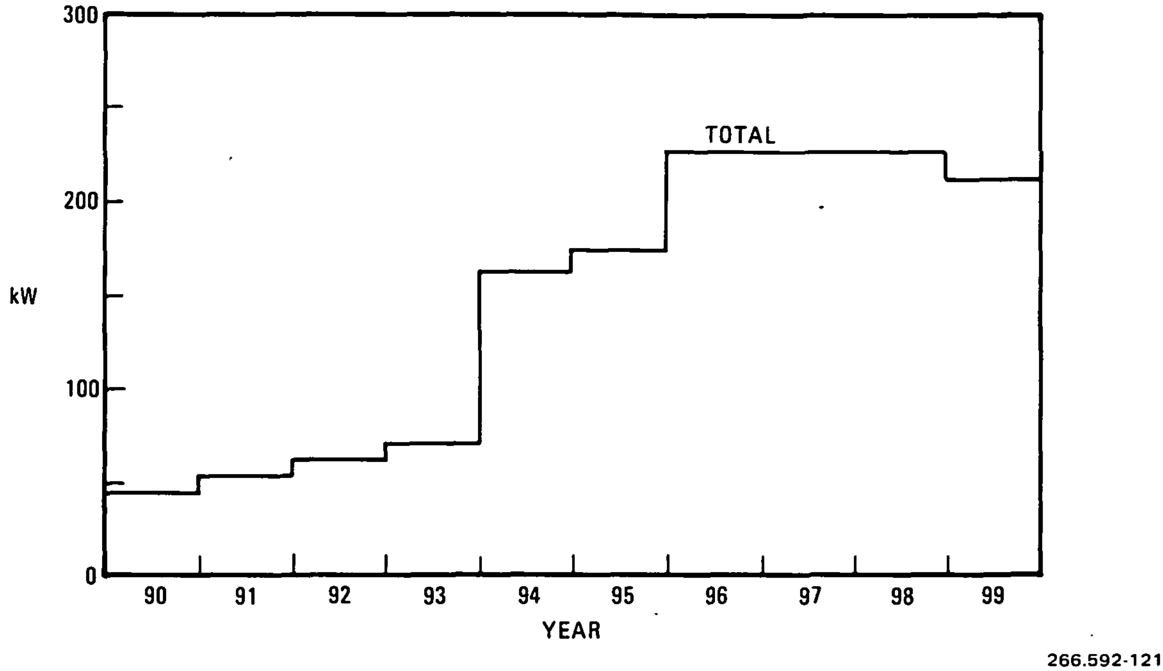

Figure 3-9. Space Station Heat Rejection Requirements

One of the key issues regarding the thermal management subsystem is whether to use current state-of-the-art technology (pumped liquid loop) on the initial Space Station facility and then shift to a more advanced system (augmented heat pipe concept) for example, or go direct to the more advanced system immediately.

Although significant work is currently underway on advanced thermal management concepts, heat pipe designs, and modular space constructable radiator configurations, it is not apparent at present that a low risk advanced design with proven hardware will be ready for the 1990 time period. By using a more current state-of-the-art system initially, a test bed will be available for proving out the more advanced system and then it can be used for subsequent growth. A decision on this issue cannot be made until the development work that will be accomplished over the next several years can be evaluated.

Regardless of the initial design employed, the final configuration must be versatile. For satisfying the Space Station's waste heat rejection requirements, the idea of a thermal utility has evolved. The prime element of this utility concept is a thermal bus which provides the heat transport function at a given temperature level or levels. The functions of the thermal bus include:

a. Provide a near constant thermal control source which is insensitive to variation in thermal load from the Space Station electrical, life support, mechanical, scientific, experimental and production equipment.

b. Provide interfaces for payload heat loads. Provide for change in payload (connection and disconnection) without affecting other payloads.

c. Transport waste heat from the sources to the radiator system for rejection.

d. Provide thermal management system characteristics which permit on orbit maintenance and repair, reconfiguration, and growth.

Several industry studies have been conducted concerning the application and evaluation of thermal bus concepts (References 3 and 4). In Reference 4, a number of concepts involving two-phase flow (which meets the near constant thermal control source requirements) are evaluated. It was concluded that the mechanically pumped concept has the lowest development risk and shortest lead time. The alternative choice is the capillary pumped concept because of its passive nature and long life potential, but a longer lead time and greater risk is involved.

3.2.2.2 Options and Trades. A schematic of the thermal utility concept employing a mechanical pump is presented in Figure 3-10. This figure shows the modular characteristics required and the interfaces between the bus and the waste heat sources and the radiator rejection system. The heat pipe radiator and contact heat exchanger assembly shown is based on the concept of Reference 5 which is currently under development. The concept of Reference 5 includes a liquid heat exchanger in contact with the evaporator sections of the heat pipe radiator panels. This implies that either 1) the main bus is an all liquid loop, or 2) a condensing heat exchanger is used in the main bus (two phase) and the cold side is part of an all liquid loop which transports the heat from the bus to the heat rejection hardware.

In Figure 3-11, however, a vapor to liquid condensing heat exchanger is shown in contact with the evaporator sections of the heat pipe radiator panels. This scheme eliminates an intermediate all liquid loop and as a result, the heat pipe panels can operate at a higher temperature. Further study and evaluation is required in this area to determine the most efficient and reliable method of transporting the heat from the thermal bus to the radiator panels.

a. Reliability. As noted in Figure 3-10, only one of two redundant loops are shown. Reliability of the thermal management system is essential, and the use of excessive crew time in maintenance and repair of the system is to be avoided. The studies of Reference 4 included a design goal of 0.99 probability of no failure for a 10 year life. To obtain this objective for a large system, a redundant component/redundant system approach is required with a minimum program of component replacement.

b. Operating Temperature. For the Space Station application, the thermal bus functional characteristics of being able to 1) add or subtract heat at several locations, and 2) at a near constant temperature regardless of the quantity or distribution of heat added or subtracted are highly desirable. Heat sinks and sources, however, are frequently needed at various temperature levels as follows:

4C (40F)	- manned module heat exchangers
20-40C (68-104F)	- electronic/electrical equipment
120C (248F)	- space processing furnaces

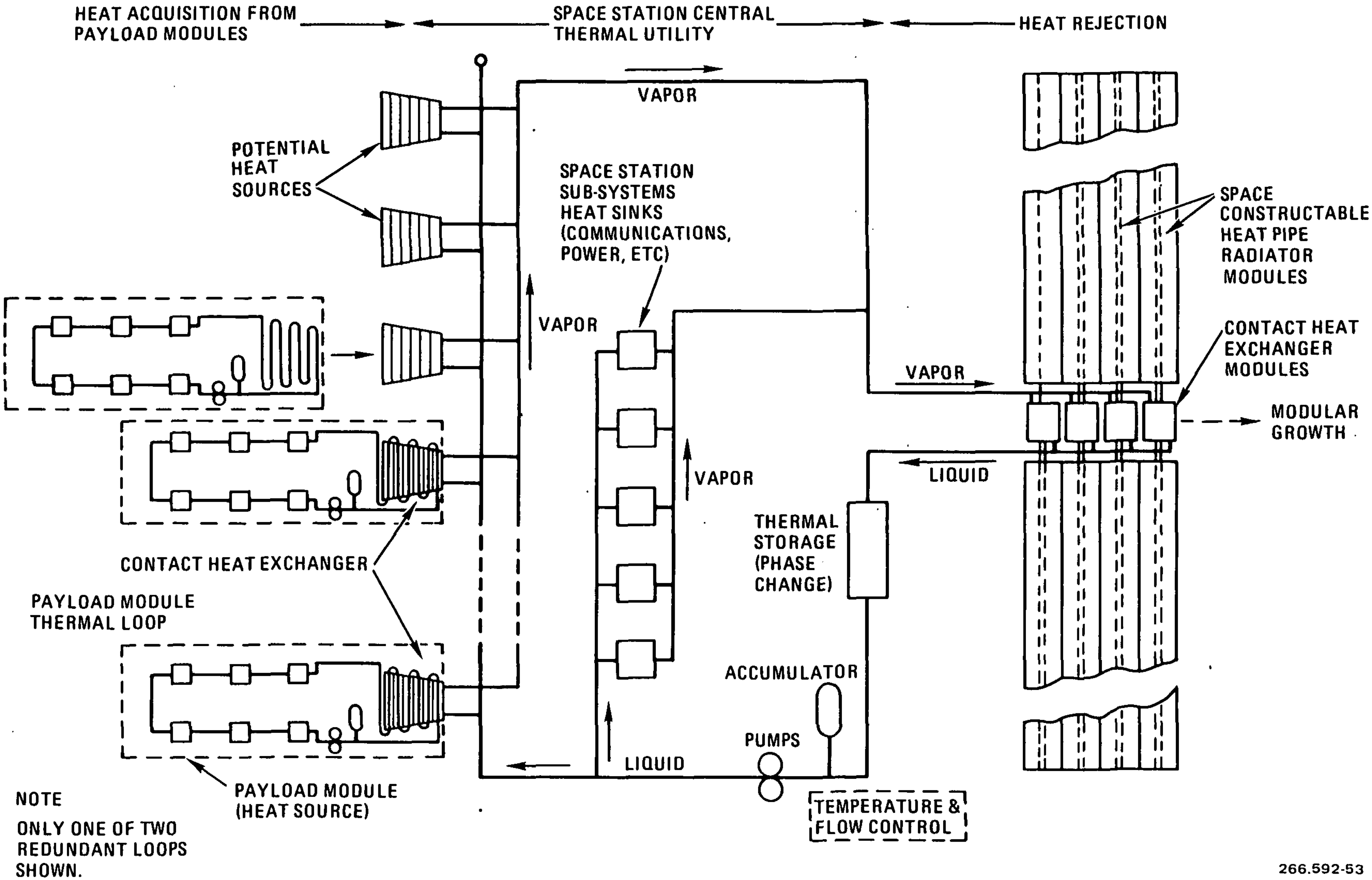

Figure 3-10. Space Station Pumped Fluid (Two Phase) Thermal Management System Schematic

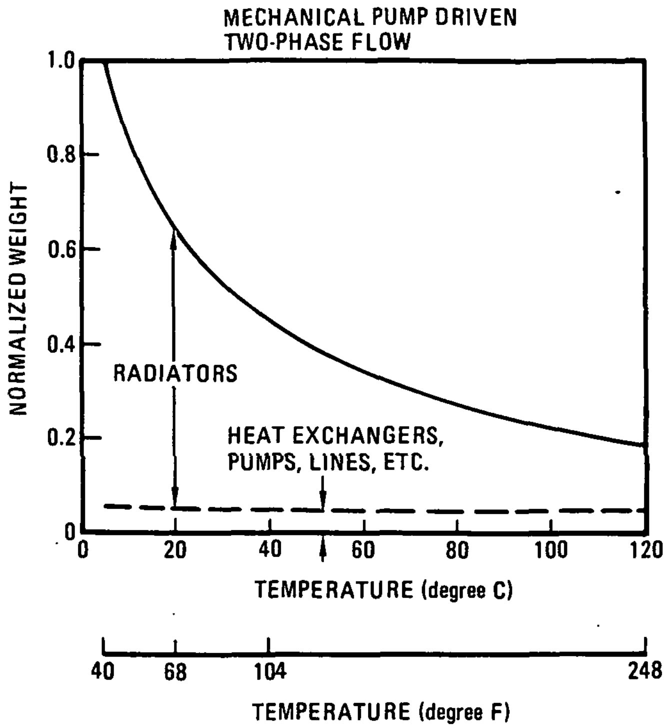

Figure 3-11. Thermal Management Subsystem Weight Sensitivity to Temperature

It is very likely that a single thermal bus concept will not be optimum. The temperature level at which the thermal management system operates has a significant effect on subsystem weight. Figure 3-10 shows a typical normalized variation in weight of a two phase mechanical pump driven system as a function of operating temperature based on the results of Reference 2. As operating temperature increases, the decrease in weight is almost totally due to the decrease in the radiator hardware required. It is apparent that for a large amount of waste heat from space processing furnaces, a separate thermal bus at 120C (148F) operating temperature could significantly reduce the total radiator hardware required compared to a single bus concept at a lower operating temperature. The addition of a separate bus, however, increases the complexity of the overall system and requires the development and construction of both high temperature and low temperature heat pipe radiator panels. Further study is required in this area.

c. Fluid Selection. To obtain a near uniform thermal control source necessitates the use of two-phase flow where the liquid and vapor flow lines transport the heat over large distances. The fluid used in this concept must have a relatively high vapor pressure at the design operating temperature. If the vapor pressure of a particular fluid is too low, the line sizes or pressure losses are such that the fluid cannot be used. The results of several industry studies show that ammonia is the superior working fluid in terms of system weight and performance over the range of conditions under consideration. Its toxicity and flammability, however, make it unsuitable for use in pressurized manned modules. Although

water can be employed at temperatures of about 40C (104F) and above, at lower temperatures, it is not attractive because of its low vapor pressure. In fact, no suitable fluid has been identified for use in a large two-phase system in a manned cabin at low temperatures. Thus, the thermal bus with ammonia as the working fluid would be located in unmanned unpressurized areas, and manned modules will include their own pumped liquid (water) loop system that interfaces with the thermal bus through contact heat exchangers as indicated in Figure 3-10.

d. Thermal Disconnect. The large multi-mission Space Station and its increasing space heat rejection requirements means that on-orbit service and replacement capability is a must. Heat generating modules which have completed their mission or have become defective must be removed and/or replaced. This operation implies the need for an efficient thermal disconnect. The unit or system must achieve positive and efficient thermal coupling and reliable and interference-free decoupling without spillage of fluid and without interfering with other heat sources and sinks in the system. Convair has analyzed, designed, and tested a conceptual quick disconnect which can satisfy these needs (Reference 6). This disconnect, shown in Figure 3-12, consists essentially of a liquid side of multiple loops of thin-wall flat tubing and a heat-sink/source side consisting of a thermally-conductive billet

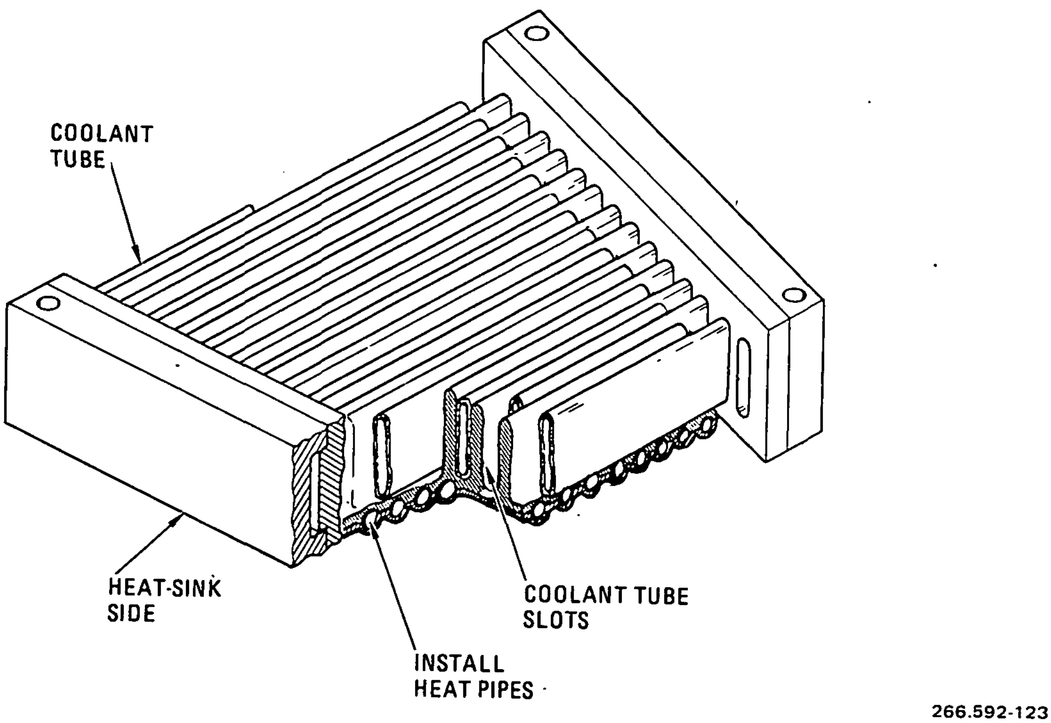

Figure 3-12. Spill Free Thermal Disconnect

containing multiple parallel milled slots. The liquid side tubing loops are locked into the heat-sink/source slots by means of the coolant pressure. Local depressurization of the coolant permits connection or separation. On the billet side of the disconnect, liquid/vapor passages are provided for the cooling or heating functions as shown. The liquid side tubing could be designed for operation in a two-phase flow system. This is the type of contact heat exchanger shown schematically in Figure 3-10.

This type of disconnect system can be used for the man tended free-flyer function as shown in Figure 3-13. Here, replacement packages or units are carried in a servicing module from the manned Space Station to the free-flyers in neighboring orbits using the OTV or the Teleoperator Maneuvering System.

3.2.2.3 Technology Needs. Significant development work is required in the thermal management system area as follows:

a. Continue development of the pumped two-phase fluid thermal management system. Methods must be developed for efficient collection, transport, and rejection of waste heat at different temperature levels.

b. Develop condensing heat exchangers for interfacing with the evaporator sections of the space constructable heat pipe radiator panels.

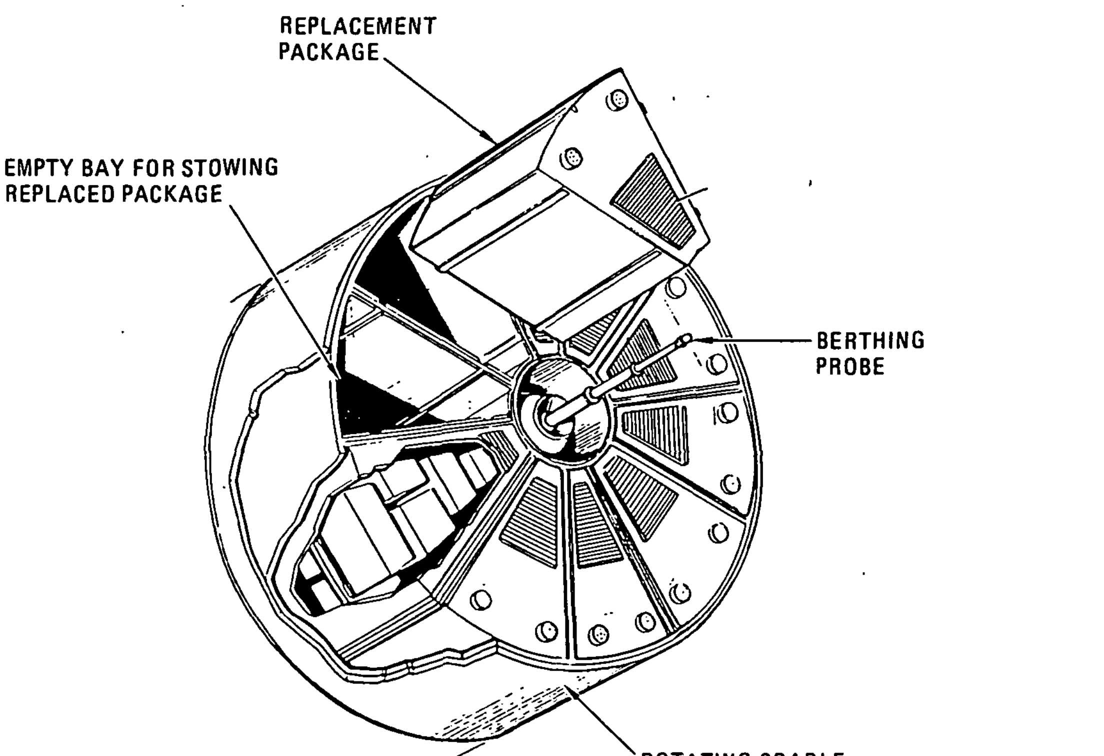

Figure 3-13. Servicing Module with Quick Disconnect Units for Free-Flyer Maintenance

c. Identify a suitable fluid for use in a two-phase system in a manned pressurized module.

d. Continue development of methods and hardware for thermally connecting and disconnecting equipment and modules without spillage or interfering with other operations.

3.2.3 FLIGHT AND STRUCTURE CONTROL. Two considerations predominate in the control of a large space station. The first consideration relates to the large disturbance torques associated with a large body in low earth orbit arising principally from gravity gradient and offset atmospheric drag. It is estimated that these disturbances will be severe even when the station is maintained in a favorable local vertical-local horizontal orientation and that the penalties in terms of attitude control propellant and/or angular momentum exchange devices will be prohibitive for any non-favorable orientation. If the disturbance estimates for large stations are correct, it follows that there will not be any maneuvering of the entire station to accommodate specific payloads. As for smaller, early stations, the same nonmaneuvering approach is taken for definite technology needs. The second major consideration for a very large and structurally complex station is that of low frequency flexible structural modes. These modes are expected to be within the desired bandwidth of the attitude control system which would cause stability problems if conventional control laws were used. In addition, the modal oscillations could have adverse effects on payloads and, in extreme cases, might build up and cause structural damage.

3.2.3.1 Disturbance Management. The conventional techniques for management of disturbing torques on a spacecraft are: 1) countering them with reaction control; or 2) storing them in an angular momentum exchange device. Since some disturbances are oscillatory, gravity gradient in roll and yaw for example, they can be stored in a momentum device for half a cycle and then dumped to counter the other half cycle. Of course, some disturbances have bias or secular components in inertial coordinates which cannot be exchanged but are stored and then dumped by the RCS. Another approach which is quite attractive for a space station is to use the momentum device for short-term control and then misalign the vehicle principal axis so as to dump any stored momentum to gravity gradient. This would work very well in the pitch axis where the disturbances tend to be secular.

3.2.3.2 Momentum Exchange Hardware. Although large space system designs often show the need for momentum exchange devices with a capacity of at least 20,000 N-m-sec, there is no hardware available today to meet this requirement. Since the Skylab control moment gyro (CMG) at about 3000 N-m-sec is the largest capacity device available, large system designs often show a dozen or so Skylab CMGs for momentum management. It would appear that these CMGs have been used conceptually mostly by default: they are complex and have many mechanical bearings to limit life. There have been some recommendations to develop new CMGs with magnetic suspensions for bearings but this is not an ideal solution since the capacity problem would remain. Large capacity double gimballed CMGs with sufficiently rigid gimbal rings would have a significant weight problem. The annular momentum control device (AMCD) holds the promise of meeting the needs of large space systems. This device consists of a magnetically suspended composite ring that is rotated to absorb angular

momentum. Since the ring provides the maximum angular momentum per unit mass, the weight is much less than for a CMG with the same storage capacity. The weight may be estimated by the following: H/M = 60R newton meter sec per kilogram where R is the radius of the ring in meters. Thus, an angular momentum capacity, H, of 20,000 N-m-sec could be achieved with a mass M of about 180 kg (397 lb) if the ring radius were 1.83 m (6.0 ft). The AMCD is still in the relatively early stages of development and intensified activity is required to bring the device to flight readiness. Life test requirements dictate that advanced development activity should begin as soon as possible.

3.2.3.3 Flexible Structure Control. The potential for oscillatory buildup in low frequency space structure can be illustrated by assuming a structure with a 0.05 Hertz (0.314 rad/sec) first mode and a damping ratio of 0.001. When disturbed, this mode will oscillate with a decay envelope time constant of 3185 seconds or about 53 minutes. In a 92-minute orbit the structure would experience a thermal shock twice an orbit as it went between sun and shade about every 46 minutes. A decay time constant which is longer than expected disturbances does not allow an oscillation to damp out between disturbances and additive behavior could result in very large amplitudes.

Considerable effort has been expended in recent years on the development of advanced control techniques which would provide precision high performance active structural control. However, reconsidering the above example with a local velocity feedback (LVFB) control device providing a damping ratio of only 0.01, results in a decay envelope time constant of 5.3 minutes which is sufficiently fast to prevent any possible additive buildup. LVFB is a simple damping technique wherein structural rotational rate is fed directly into an actuator.

The influence of structural oscillations on sensitive payloads should be reviewed for specific configurations. It is expected that the oscillation isolation required for other disturbances, such as thrusting for velocity makeup, can be accommodated by simple active damping techniques. Thus, the modest active damping performance attainable with LVFB should be adequate for the space station requirements which are not ultra high precision.

The above has not considered the effect of low frequency modes on the stability of the attitude control system. There are two possible approaches to this problem. The first is to use a low bandwidth attitude system which would be compatible with nonstringent pointing, and the second is to use a simple rigid body state estimator. This estimator combines heavily filtered rate gyro information with integrated control torque commands to form a stabilizing input that ignores modal oscillations.

Use of AMCDs instead of CMGs greatly simplifies control system management during growth of the system. Whereas CMGs require complex computation to account for the fact that they can act in any of three axes, an AMCD is essentially a single axis device which could be operated in parallel with other AMCDs with only a gain change in the control system computation. In addition, low bandwidth, modest performance attitude control systems are not extremely sensitive to changes in system growth such that only simple gain changes can accommodate such growth including Orbiter docking.

Modest performance simple active damping is also quite insensitive to the particular low frequency structural dynamics on which it operates. Therefore, it is practical to preinstall the active dampers on flexible appendages such that when they are added to the system, their low frequency oscillatory tendencies are already accounted for on an individual basis.

3.2.3.4 Flight Control System. The modest performance flight control system for a space station does not present any new problems in the areas of attitude sensing, computation, or navigation. An inertial reference unit for short-term attitude with earth sensing update to remove long-term drift will meet the requirements. Altitude data on ground tracking can monitor altitude/velocity loss due to atmospheric drag. The propellant for altitude/velocity makeup will be appreciable. This leads to a possible requirement for efficient thruster installation since any plume impingement losses will increase the propellant requirements to even greater values.

3.2.3.5 Technology Needs Summary. The key technology need for space station attitude control is development of a suitable large angular momentum exchange and storage device. Life test considerations make this an especially pressing need. In addition, the state of the art in modest active control of structure is deficient in two respects: 1) although local velocity feedback is relatively simple, there has not been enough practical experience with it; and 2) there is a lack of components (sensors and actuators) for implementing low frequency active structural control.

3.2.4 COMMUNICATIONS AND TRACKING

3.2.4.1 Communications

3.2.4.1.1 Overview. The communication portion of the Communications and Tracking Subsystem will have many links as shown in Figure 3-14. The following specific communication links have been identified:

a. A ground link through a relay satellite. This link will utilize the NASA tracking and data relay satellite system (TDRSS) during the first half of the 1990s and its evolutionary successor, the tracking and data acquisition system (TDAS), after 1995.

b. An emergency-to-ground link for use in case of a relay satellite system failure.

c. A direct-to-ground link is required by certain experiments.

d. A link with the shuttle for rendezvous and docking purposes.

e. Manned communications during extra-vehicular activity (EVA).

f. Possible communication with a second space station.

g. Two-way communication with a free-flyer satellite.

h. Communication with an OTV or TMS.

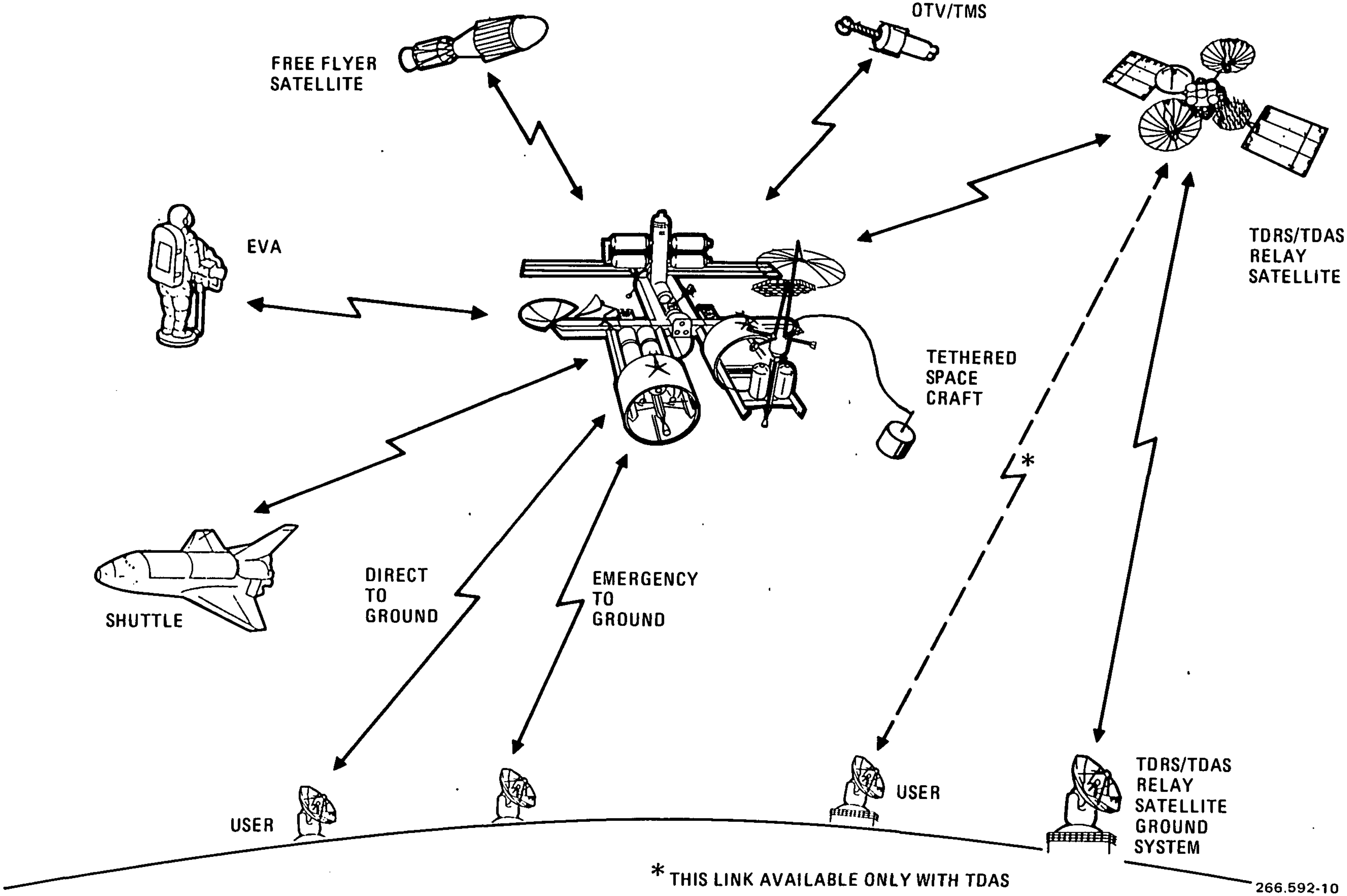

Figure 3-14. Space Station Communication Links

The communications system will evolve from a TDRSS compatible system (pre-1995) to a TDAS compatible system (post-1995). The technology necessary for the communications system will not be a pacing item for space station development. Most technology will develop and mature as a result of other programs (such as TDAS). There are, however, specific areas where R&D emphasis is required and these technologies are discussed in paragraph 3.2.4.1.5.

3.2.4.1.2 Communication system requirements

a. TDRS Compatibility (Pre-1995). The TDRS system has been developed by NASA specifically to support vehicles in low earth orbit such as space stations. It provides near continuous data coverage using synchronous satellites since providing an equivalent area of coverage using ground stations is not feasible for both economic and political reasons.

   Four general classes of telecommunication links are provided by TDRSS. Forward service links provide the signal paths from the White Sands Ground Terminal (WSGT) through the TDRS to NASA satellites orbiting the earth. Return service links provide the signal paths from the NASA satellites through the TDRS to the White Sands Ground Terminal. The spacecraft is shown in Figure 3-15. Utility links between WSGT and the TDRS provide for normal satellite operations.

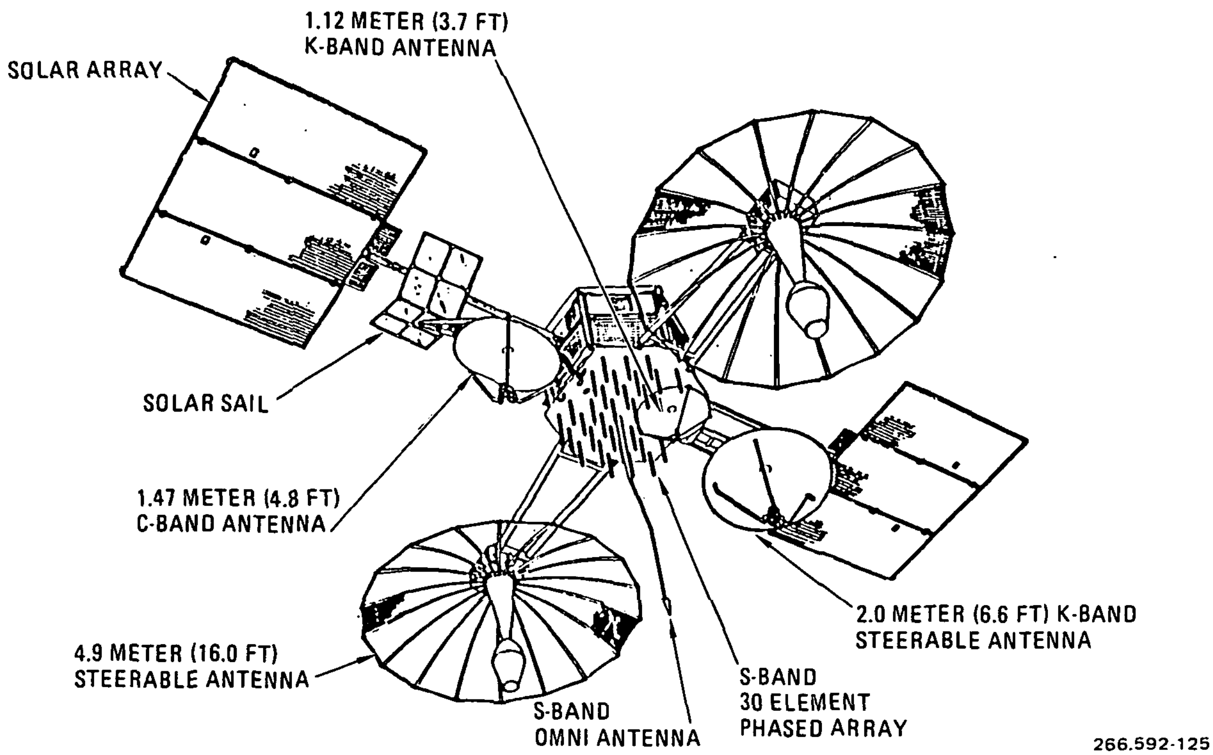

Figure 3-15. Tracking and Data Relay Satellite (TDRS)

Three types of TDRSS forward and return service links are provided: K-band single access (KSA), S-band single access (SSA) and multiple access (MA). KSA and SSA forward and return links operate between the TDRS and the users through two 4.9M deployable dishes. SSA forward (SSAF) links operate in the unified S-band frequency allocation currently assigned to the NASA space tracking and data network (STDN) for transmissions to orbiting satellites. The SSA return (SSAR) links receive signals in the unified S-band allocation jointly shared by NASA and military satellites for the transmission of telemetry data from space to ground. The MA links operate at S-band in the forward and return direction using electronically steerable phased arrays on the TDRS for transmission and reception. The maximum data rate for each link is listed in Table 3-5. Thirty-two NASA communication links are provided simultaneously in the TDRS mode of operation consisting of five forward service links (2 KSA, 2 SSA, and 1 MA), twenty-four return service links (2 KSA, 2 SSA, and 20 MA) plus the three utility links. It is expected that the TDRSS will be the prime carrier of data from the space station to ground.

The TDRSS consists of two operational spacecraft and an on-orbit spare. Each operational spacecraft must be able to use the White Sands Ground Terminal and requires the spacecraft to be positioned less than 180 degrees apart (referenced to the center of the earth). As shown in Figure 3-16, there is a zone-of-exclusion located over the Indian Ocean in which TDRSS coverage is not possible. A spacecraft must orbit to exceed 1200 km altitude to pass over this zone-of-exclusion.

b. TDAS Compatibility (Post-1955). The TDAS (Figure 3-17) is the next generation relay satellite system expected to be operational in 1995. TDAS will be fully TDRSS compatible, i.e., it will accommodate all TDRSS links. However, it has expanded capability to meet the communication needs of the mid-1990s including:

1. Five W-band (60 GHz) single access antennas are provided for high data rate users.

2. Two laser telescopes are used for very high data rate return signals.

Table 3-5. Maximum TDRSS Data Rates for One Channel

SERVICE	MAXIMUM DATA RATE FORWARD LINK	MAXIMUM DATA RATE RETURN LINK
MA	10 KBPS	50 KBPS
SSA	300 KBPS	12 MBPS
KSA	25 MBPS	300 MBPS

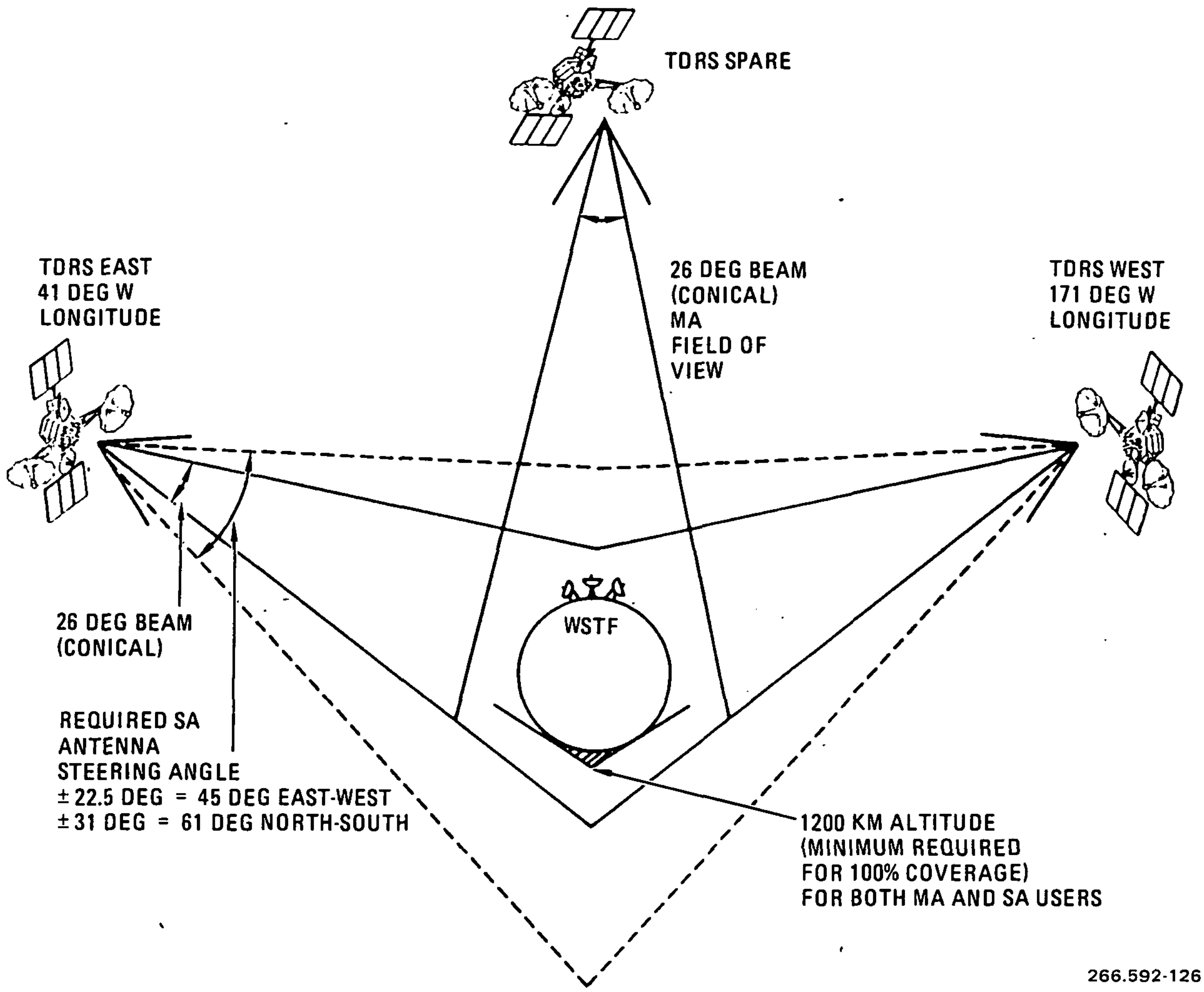

Figure 3-16. Geometry of TDRS Placement Showing Zone-of-Exclusion

3. Nine K_A-band (20-30 GHz) antenna beams are directed at CONUS for distribution of data direct to the ground user without going through the White Sands Ground Terminal. Five of these are fixed (Sunnyvale, White Sands, Colorado Springs, Houston and Washington, D.C.) and four are movable.

4. The MA spacecraft antenna will be redesigned to give approximately 3 dB more gain, resulting in better beam-forming performance and reduced user EIRP requirements.

The maximum data rates for each TDAS channel are shown in Table 3-6. All of the expanded TDAS capabilities will be used by space station and the ability to distribute data directly to a ground user (Figure 3-18), especially at high rates, will allow the flight of certain experiments that are not possible using TDRSS. Another improvement of the TDAS is reduction of the zone-of-exclusion. The satellites pass data via laser links and only one satellite has to be in view of the White Sands Ground Terminal. This allows spacing the two satellites further apart (than the TDRSS) as shown in Figure 3-19. This reduces the zone-of-exclusion

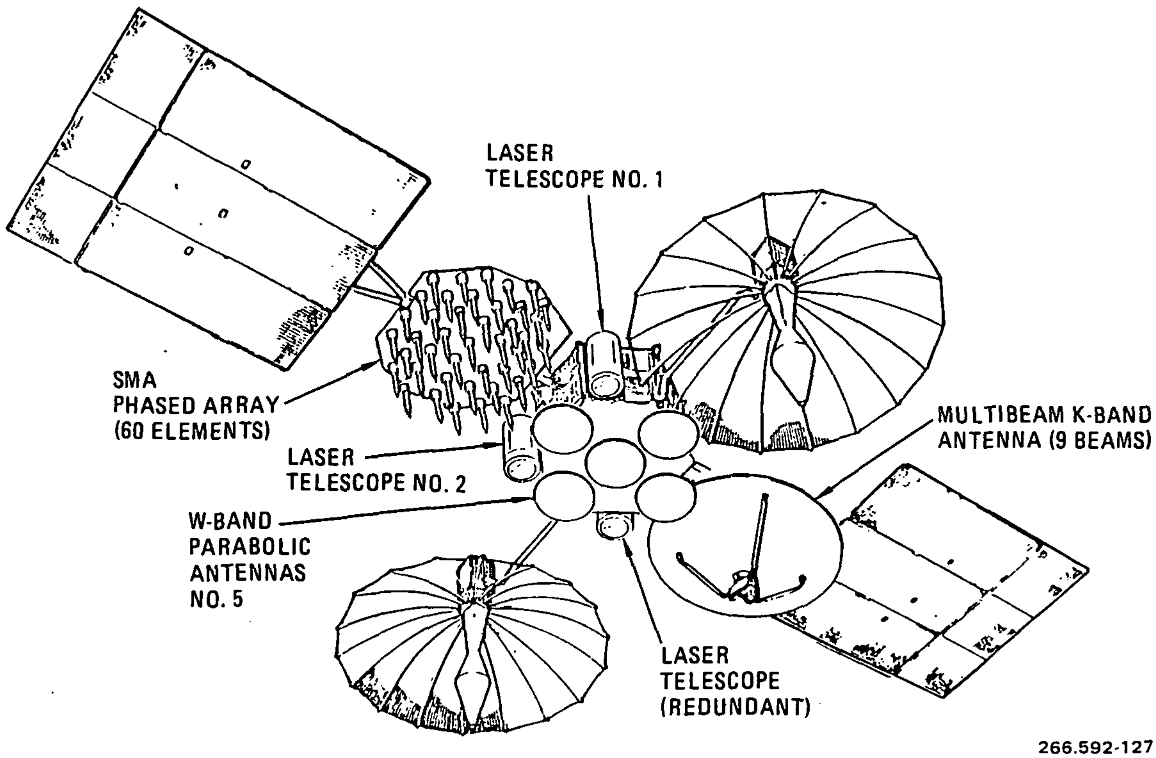

Figure 3-17. Tracking and Data Acquisition Satellite (TDAS), Showing New Features Added

Table 3-6. Maximum TDAS Data Rates for One Channel

SERVICE	MAXIMUM DATA RATE: FORWARD LINK	MAXIMUM DATA RATE: RETURN LINK
MA	10 KBPS	50 KBPS
SSA	300 KBPS	12 MBPS
KSA	25 MBPS	300 MBPS
WSA	-	10 MBPS
LASER	-	2 GBS

such that it has an altitude of only 320 km. A space station orbiting at 400 km would have continuous data coverage with 2 relay satellites. Using 3 operation relay satellites can eliminate the zone-of-exclusion and provide 100 percent data coverage for low-altitude users. As with the TDRSS, it is expected that the TDAS will be the major conduit of data to and from the space station.

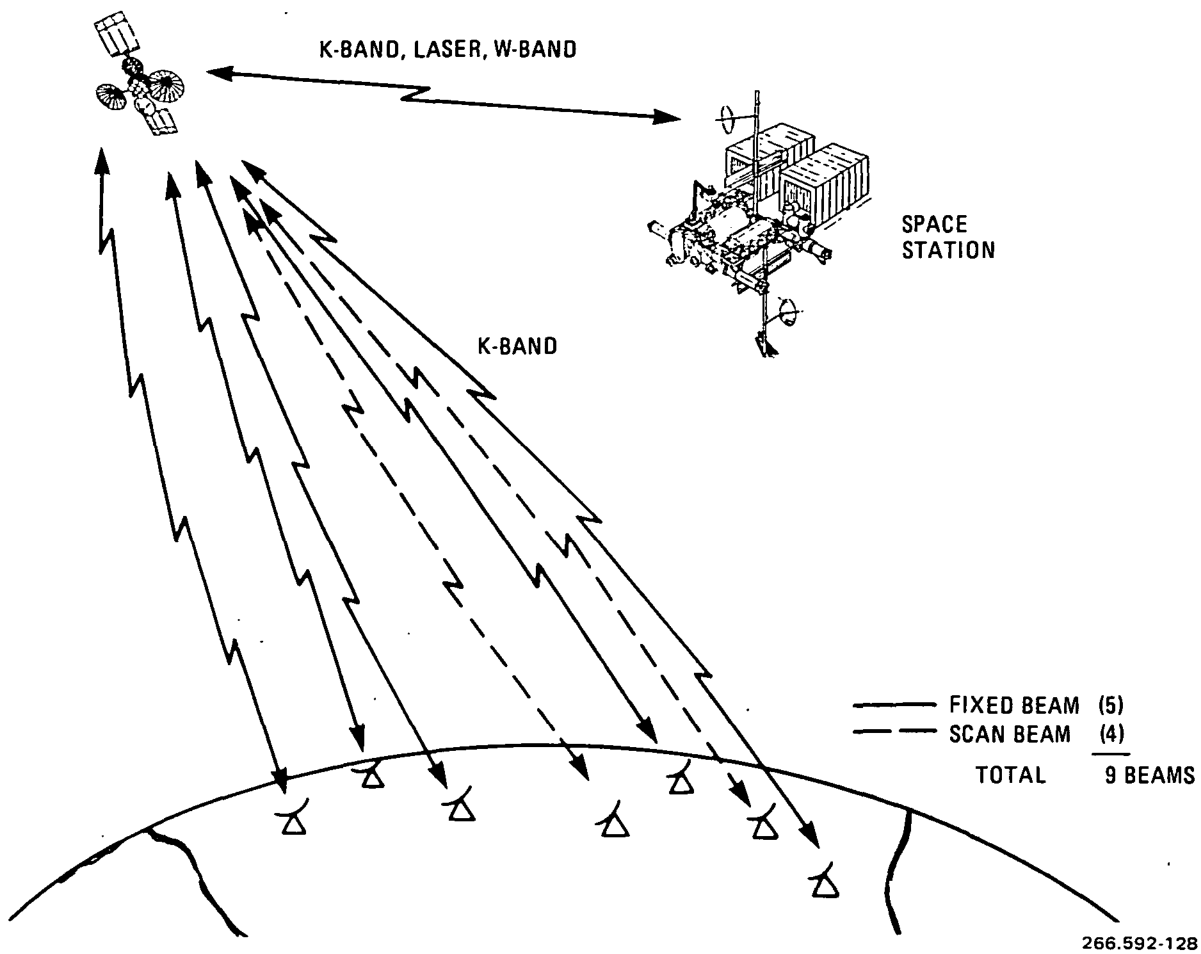

Figure 3-18. TDAS Direct-to-User K-Band Data Links

c. Payload Data Requirements. The data requirements of all potential space station payloads, both experimental and commercial, have been investigated. The data requirements for individual experiments are listed in Subsection 2.1.1 of this volume. These requirements have been summarized and are shown in Table 3-7 for those payloads with stated requirements. The science and applications payloads, specifically the Earth and planetary exploration experiments (Nos. 0100-0199), have the highest data requirements. The highest requirement is 300 MBS and exists for several experiments. The environmental observations experiments (Nos. 0200-0299) are second in data requirements with a maximum data rate of 120 MBS, although 80 percent of the experiments investigated have rates less than 42 KBS. By and large, most experiments have modest data rates easily accommodated by TDRSS and of course all experiments can be accommodated by TDAS. The six payloads that are not TDRSS compatible are listed in Table 3-8. These have data rates in excess of 200 MBS. Although the TDRSS KSA service will handle 300 MBS, only 200 MBS are allowed for payload data (on a continuous basis) because 50 MBS are allocated to platform data (item d. of paragraph 3.2.4.1.2) and 50 MBS to the transmission of data stored as the space station passes through the zone-of-exclusion (item f. of paragraph 3.2.4.1.2).

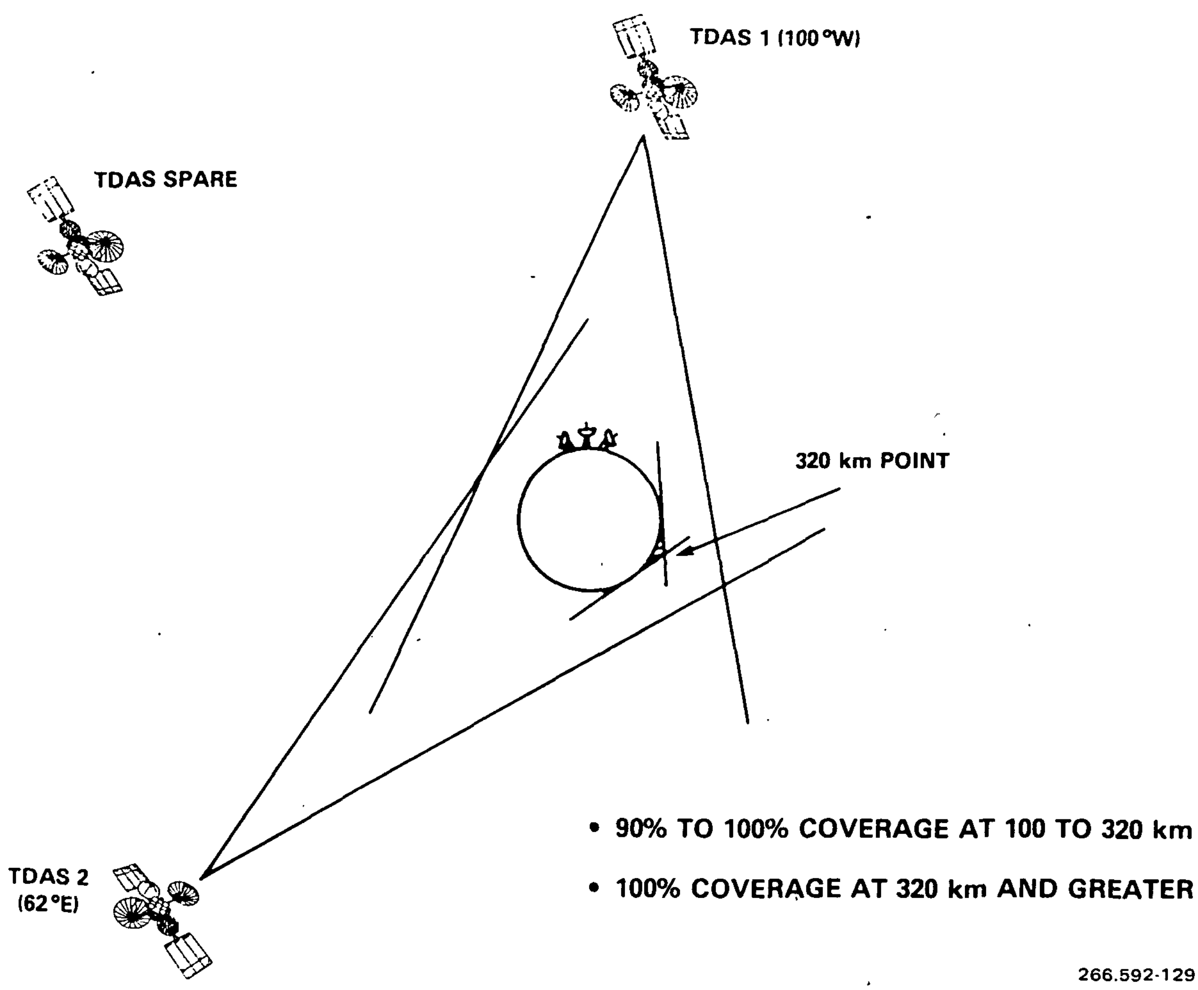

Figure 3-19. Geometry of TDAS Placement Showing Zone-of-Exclusion

One hundred and forty-nine experiments were identified as potential payloads and all but the six listed in Table 3-8 are TDRSS compatible. It is possible, however, to accommodate each of these experiments on a pre-1995 space station using one of the following methods:

1. Use of both TDRS single access antennas simultaneously. This would require all other users of a particular TDRS to use the SMA service.

2. Development by the experimentor of video compression techniques to reduce the experiment data to 200 MBS (if this experiment is the only space station user at this time) or below (if simultaneous use of other experiments is required).

3. Addition of an experiment-to-ground RF link for direct download of experiment data over selected ground stations.

4. Leaving the data in analog form, where it will occupy much less bandwidth, and transmitting the signal to ground via the standard bandwidth (36 MHz) of another communication satellite.

Table 3-7. Summary of Experiment Data Rates

MISSION TYPES	4 DIGIT I.D. NOS.	HIGHEST DATA RATE (BPS)	2ND HIGHEST DATA RATE (BPS)	80% OF EXPTS LESS THAN (BPS)
• SCIENCE & APPLICATIONS				
Astronomy	0000-0099	42M	16M	16M
Earth & Planetary Exploration	0100-0199	300M	300M	300M
Environmental Observations	0200-0299	120M	110M	42K
Life Sciences	0300-0399	128K	128K	128K
Materials Processing	0400-0499	6K	3K	6K
• COMMERCIAL MISSIONS				
Earth & Ocean Observations	1000-1099	-	-	-
Communications	1100-1199	100M	1M	1M
Materials Processing	1200-1299	10K	10K	10K
Industrial Services	1300-1399	-	-	-
• TECHNOLOGY DEVELOPMENT				
Materials & Structures	2000-2099	1K	1K	1K
Energy Conversion	2100-2199	-	-	-
Computer Science & Electronics	2200-2299	1K	1K	1K
Propulsion	2300-2399	-	-	-
Control & Human Factors	2400-2499	-	-	-
Space Station Systems/Ops	2500-2599	1K	-	1K
Fluid & Thermal Physics	2600-2699	4K	1K	1K

Table 3-8. Experiments Identified as Having in Excess of 250 MBS Data Requirements

GDCD EXP. NO.	PAYLOAD NAME	STATED DATA RATE
0151	Detection and Monitoring of Episodal Events	300 MBS
0172	Operational Land Systems	300 MBS
0177	Geoscience - Geology Remote Sensing	300 MBS
0182	Z - Hydrologic Cycle Pri	300 MBS
0183	Z - Special Coverage	300 MBS
0184	Z - Continuous and Special Coverage	300 MBS

5. Bulk recording of the data, probably in analog form, and transporting it back to ground on the next Shuttle visit.

In summary, 97 percent of the experiments investigated are TDRSS compatible and the remaining six could be handled by extraordinary means.

d. Space station data requirements. The space station communication links are shown in Figure 3-14 and the corresponding data rates are presented in Table 3-9. The data bandwidth requirements are estimates intended to be used for selection of the proper RF links.

1. Ground via TDRSS. In formulating the relay satellite return links, 50 MBS was allowed for platform data. This number was derived as follows:

   2 - digital video at 22 MBS each

   4 - duplex voice at 15 KBS each

   2 MBS housekeeping data

   This totals to 46.064 MBS, so 50 MBS was allowed. The allocation for each video link of 22 MBS is for slow scan high definition television. The term slow scan is referenced to commercial TV (30 FPS) and is still quite adequate for any expected motion to be encountered in the space station. With 50 MBS of platform data and up to 200 MBS of experiment data, a total real time data maximum of 250 MBS is established. This will allow for data recording when passing through the zone-of-exclusion and retransmission later, and still not exceed the TDRSS 300 MBS limit for a single KSA channel. The requirement for the uplink from the ground is:

   1 - digital video at 22 MBS

   4 - duplex voice at 16 KBS each

   250 kHz digital data

   This total is 22.266 MBS and 25 MBS was allowed.

2. Ground via TDAS. Platform data requirements are the same as for TDRSS. TDAS laser links can accommodate two high data rate experiments listed in Table 3-8. The total link bandwidth allowed is:

   2 - 300 MBS experiments (laser link)

   250 MBS other experiments

   50 MBS platform data

   This gives a total of 900 MBS but this can be raised as the full bandwidth of the laser links is not being used. The uplink requirement is the same as the TDRSS uplink.

3. Experiment Direct-to-Ground. Some payloads have requested direct-to-ground links. The bandwidth would depend upon the specific experiment.

Table 3-9. Preliminary Space Station Communication Requirements

LINKS	GROUND				SHUTTLE	OTV/TMS	FREE FLYER	TETHERED SPACECRAFT	EVA
	VIA TDRSS PRE 1995	VIA TDAS POST 1995	EXPERIMENT DIRECT TO GROUND	EMERGENCY TO GROUND					
FORWARD LINK FROM SPACE STATION	2-DIG. VIDEO 4-DUP. VOICE S/S TLM EXPO DATA TO 200 MBS TOTAL UP TO 250 MBS	2-DIG. VIDEO 4-DUP. VOICE S/S TLM EXPO DATA TO 700 MHZ TOTAL UP TO 750 MHZ	EXPERIMENT DEPENDENT– MAY BE AS HIGH AS GIGABITS	2-DUPLEX VOICE S/S TLM TOTAL 300 KBS	2-DUPLEX VOICE DATA TOTAL 48 KBS	2-DUP. VOICE CMD. & DATA UPLOAD TOTAL 48 KBS	CMD. & DATA UPLOAD TOTAL 30 KBS	EXPERIMENT DEPENDENT– BUT PROBABLY KILOBITS	1-DUP. VOICE CMDS. 32 KBS (IF DIGITAL LINK IS USED).
RETURN LINK TO SPACE STATION	1-DIG. VIDEO 4-DUP. VOICE S/S CMDS & DATA UPLOAD EXP. CMDS & DATA UPLOAD TOTAL 25 MBS	1-DIG. VIDEO 4-DUP. VOICE S/S CMDS & DATA UPLOAD EXP. CMDS & DATA UPLOAD TOTAL 25 MBS	NO REQUIREMENT	2-DUPLEX VOICE S/S CMDS & DATA UPLOAD TOTAL 100 KBS	2-DUPLEX VOICE DATA TOTAL 48 KBS	2-DUP. VOICE 1-DIG. VIDEO TLM TOTAL 23 MBS	TLM TOTAL 256 KBS	EXPERIMENT DEPENDENT MAY BE AS HIGH AS GIGABITS	1-DUP. VOICE TLM 48 KBS (IF DIGITAL LINK IS USED)

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4. Emergency-to-Ground. This link is required if a failure of the relay satellite system occurs. A total allowance of 300 KBS downlink includes 2 duplex voice links as does the uplink requirement of 100 KBS.

5. Shuttle. 48 KBS has been allowed for the exchange of voice and a modest amount of data. If video interchange is needed it can be accomplished via the relay satellite system.

6. OTV/TMS. This link has bandwidth allocation for 2-way voice and video from the OTV/TMS back to the space station based on the assumption that the vehicle will be manned. If it is unmanned, the requirement will be reduced to a small amount of telemetry from the OTV/TMS and a few commands from the space station. An assumption has been made that the primary communication link for the OTV or the TMS will not be through the space station but through the relay satellite system.

7. Free Flyer. As with the OTV/TMS, the assumption is made that the primary communication link is the relay satellite system. Only a small amount of telemetry and commands will be interchanged.

8. Tethered Spacecraft. A tethered spacecraft would have its data treated like an experiment that is on the space station, i.e., the data would use the space station data processing and communication subsystems.

9. Extra-Vehicular Activity. During EVA, the astronaut must be able to talk to the station in the duplex mode. A modest amount of telemetry must be transmitted to the station and the station must be able to transmit a few emergency commands.

As noted earlier, the data rates given in Table 3-9 are intended to be used for link selection only. Although the relay satellite requirements are formulated using the payload requirements of the research, development and production (RD&P) facility of the space station, they are considered valid for the operations and servicing (O&S) facility as well since the O&S facility will service OTVs and spacecraft having payloads that may have experiments with data rates as high as the RD&P facility.

e. Antenna Coverage. The space station will have a large number of antennas. The angular coverage requirements for the various links are given in Table 3-10. Most links are omnidirectional, but the relay satellite link and the ground links depend upon stabilization requirements of the platform. For earth stabilized missions, the relay satellite links require coverage in slightly more than the upper hemisphere and the ground links require coverage in the lower hemisphere. For sun-stabilized missions, the required coverage is omnidirectional.

Table 3-10. Communication System Antenna Angular Coverage Requirements

SYSTEM	ANGULAR COVERAGE REQUIREMENT
TDRSS/TDAS	Mission dependent. For earth stabilized missions, requirement is for coverage over slightly more than the upper hemisphere. For sun stabilized missions, omnidirectional coverage required.
Experiment-to-Ground	Mission dependent. For earth stabilized missions, requirement is for coverage in the lower hemisphere. For sun stabilized missions omnidirection coverage required.
Emergency-to-Ground	Same as Experiment-to-Ground
Shuttle	Omnidirectional
OTV/TMS	Omnidirectional
Free Flyer	Omnidirectional
EVA	Omnidirectional

f. Data Storage. The placement of the two TDRS results in the formation of a zone-of-exclusion (Figure 3-16) where communication through the TDRSS is not possible. The extent of zone varies with altitude. Figure 3-20 shows the zone for an altitude of 500 KM. The average data coverage is a function of the orbital inclination and altitude of the space station and is shown in Figure 3-21. The worst case zone-of-exclusion times are present in Table 3-11. Assuming a 300 MBS data rate, these data dropout

Table 3-11. Worst Case Zone-of-Exclusion Times for Various Altitudes and Orbital Inclinations

INCLINATION ANGLE	ALTITUDE			
	370 KM	400 KM	450 KM	500 KM
28.5°	12 Min	12 Min	10 Min	10 Min
57°	16 Min	16 Min	16 Min	14 Min
90°	32 Min	32 Min	32 Min	30 Min
98°	24 Min	24 Min	24 Min	22 Min

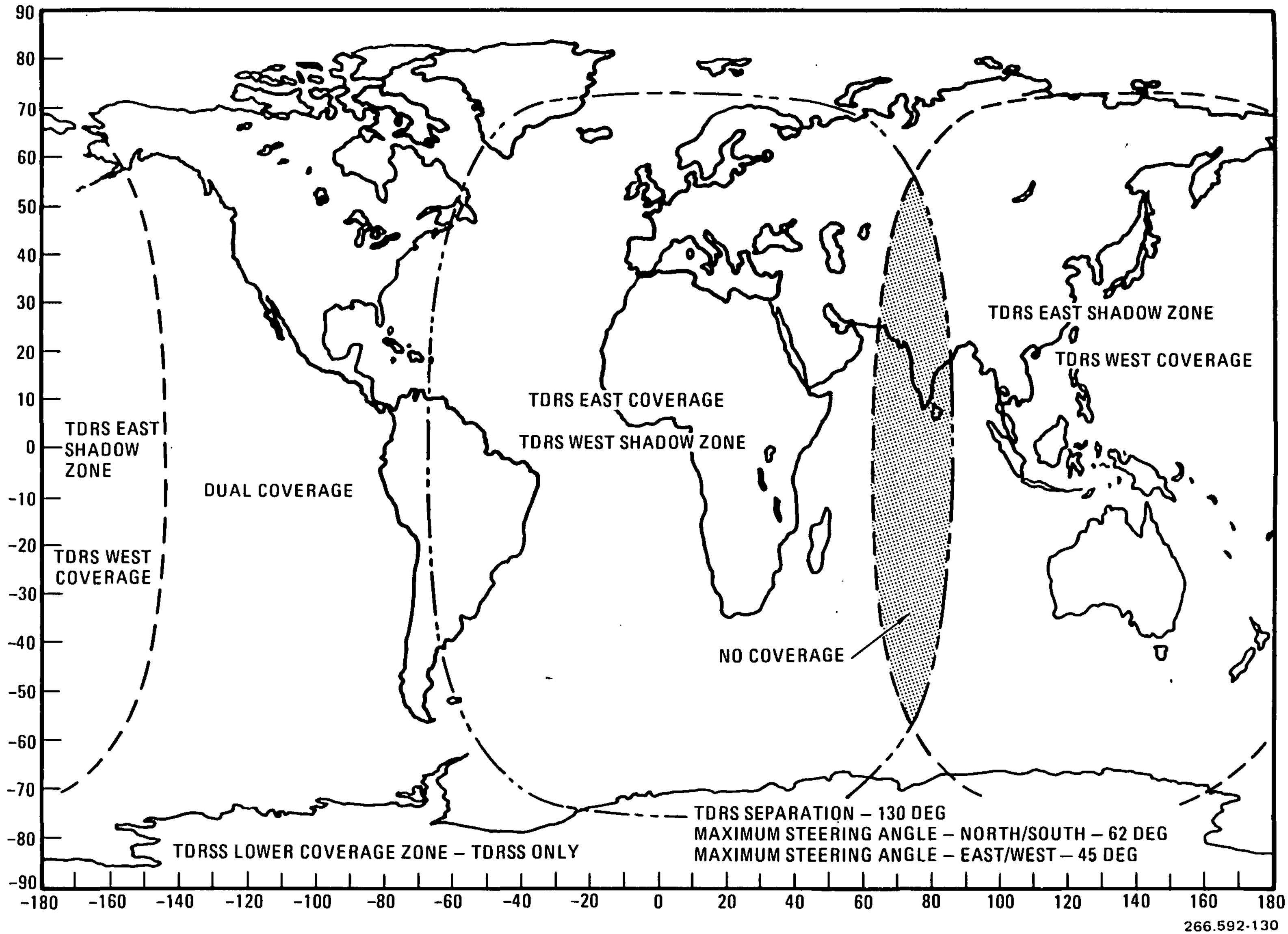

Figure 3-20. TDRSS Zone-of-Exclusion for 500 NM Altitude

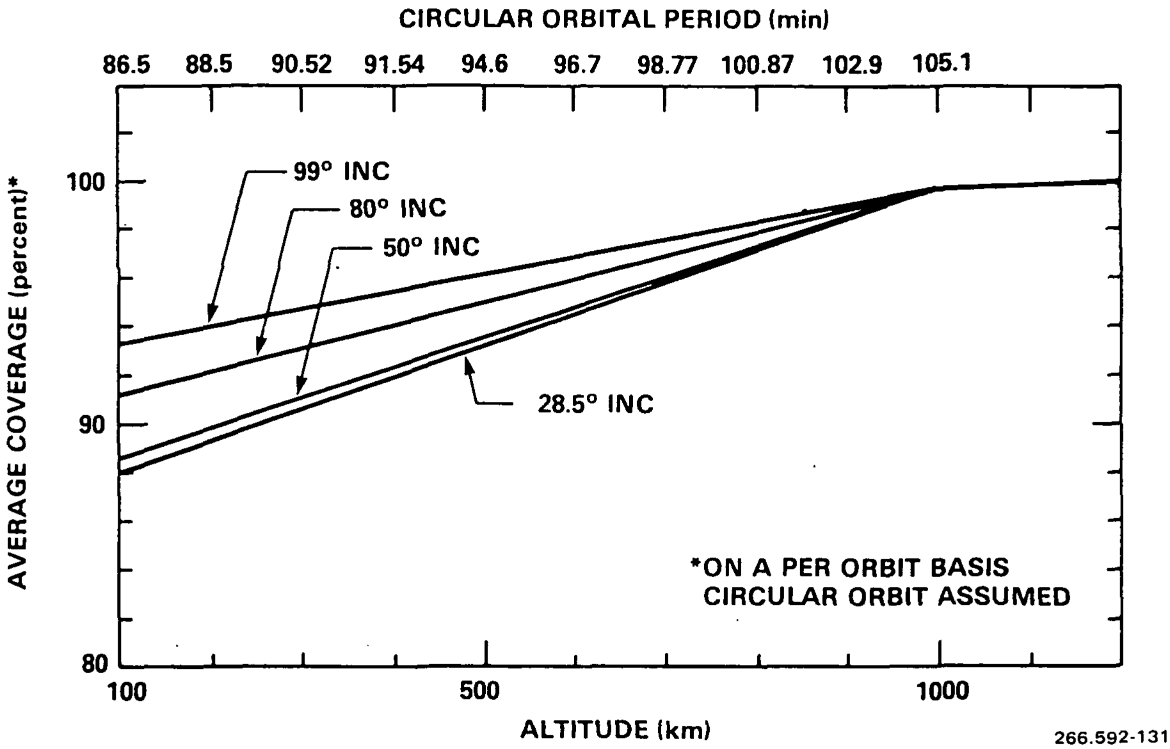

Figure 3-21. Average TDRSS Geometrical Coverage Versus Space Station Altitude for Various Orbit Inclinations

times result in a total bit storage requirement shown in Table 3-12. For a 400 km altitude orbit of 28.5-degree inclination, the requirement is approximately 2 X 10^{11} bits.

Table 3-12. Storage Capacity (in Bits) Required During Passage Through Zone-of-Exclusion for Various Altitudes and Orbital Inclinations for Data Rate of 300 MBS

INCLINA-TION ANGLE	ALTITUDE (km) 370	400	450	500
28.5°	2.2 x 10^{11}	2.2 x 10^{11}	1.8 x 10^{11}	1.8 x 10^{11}
57°	2.9 x 10^{11}	2.9 x 10^{11}	2.9 x 10^{11}	2.5 x 10^{11}
90°	5.8 x 10^{11}	5.8 x 10^{11}	5.8 x 10^{11}	5.4 x 10^{11}
98°	4.3 x 10^{11}	4.3 x 10^{11}	4.3 x 10^{11}	4.0 x 10^{11}

3.2.4.1.3 Options and Trades. The purpose of this study is to define the communication system architecture and the rationale for the selection of individual links is detailed in other portions of the section. The following are major trade studies which must be performed during the next phase of the space station study.

a. Ground Distribution During the TDRSS Era. When TDAS becomes operational, it will be possible to distribute high rate data directly from the relay satellite to the user. During the TDRSS era, however, data must go to the White Sands Ground Terminal and then be redistributed. This trade would investigate methods of accomplishing this distribution and select the best method or combination of methods. Some of the alternatives are:

   1. Spare TDRSS. The TDRS will have an on-orbit spare satellite. This spacecraft can be used to relay data from the White Sands Ground Terminal to the user (Figure 3-22).

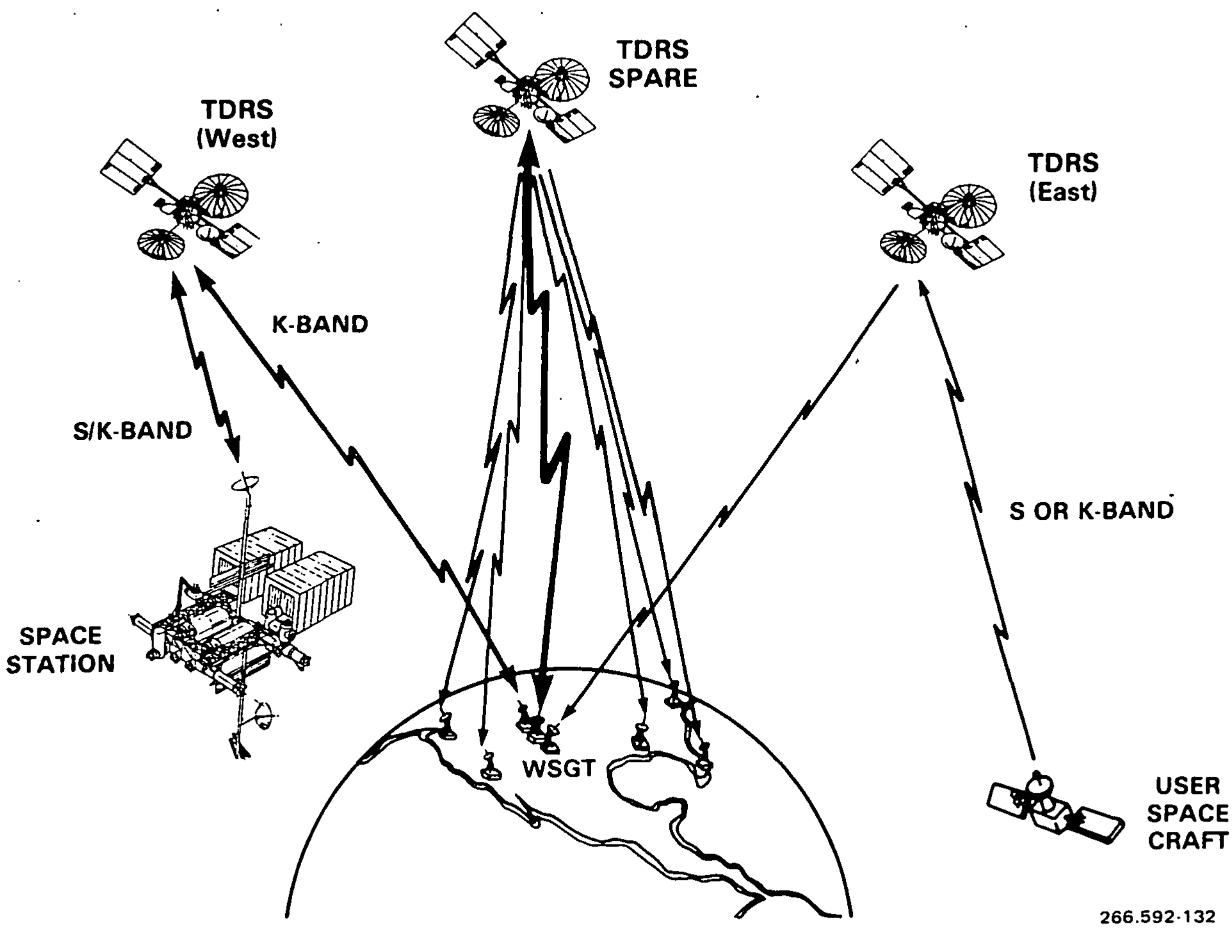

Figure 3-22. Data Distribution to User Employing the Spare TDRS

2. Domestic Communication Satellite (COMSAT). Data Distribution can also be made via a domestic COMSAT (Figure 3-23). The 36-MHz transponder is widely used in COMSATS. However, multiple transponders could be used to increase the bandwidth. These systems exist today and have a large number of existing ground terminals.

3. Terrestrial Data Distribution. Three methods of ground distribution are pictured in Figure 3-24. The Telco System would be suitable only for very low data rates. Other options are microwave and fiber optics distribution. Fiber optic data transfer between cities is just now becoming a reality on the East Coast.

b. Antenna System Configuration. With the many RF links involved, multipurpose/multibeam antennas will probably be required. Simultaneous communication on 5 to 10 links may be required in S- and K-Band. This will require the use of phased arrays with sophisticated algorithms to focus the various beams. A detailed study of all antenna system requirements and their interface with the rest of the space station must be made in order to proceed with the detail design of the communication

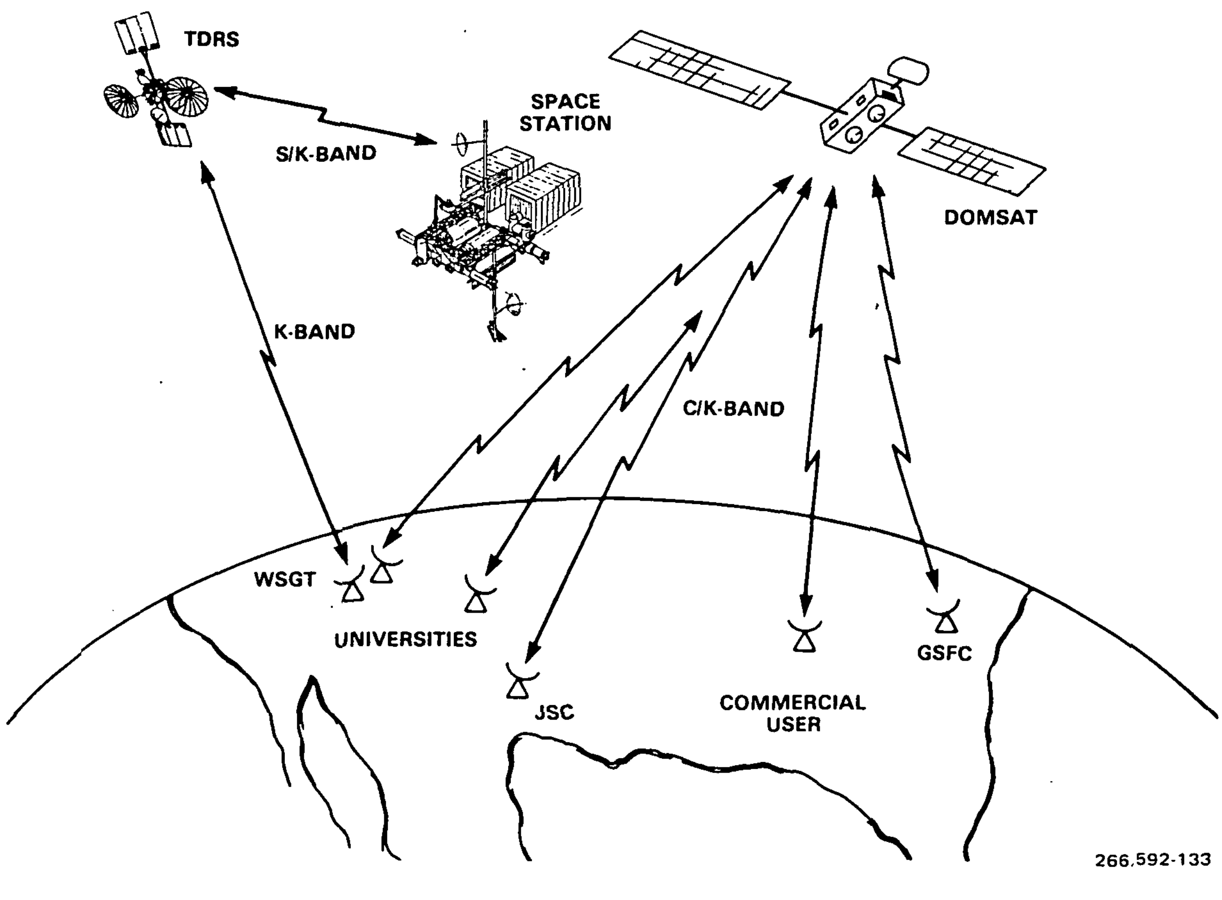

Figure 3-23. Data Distribution Using Domestic Communication Satellite

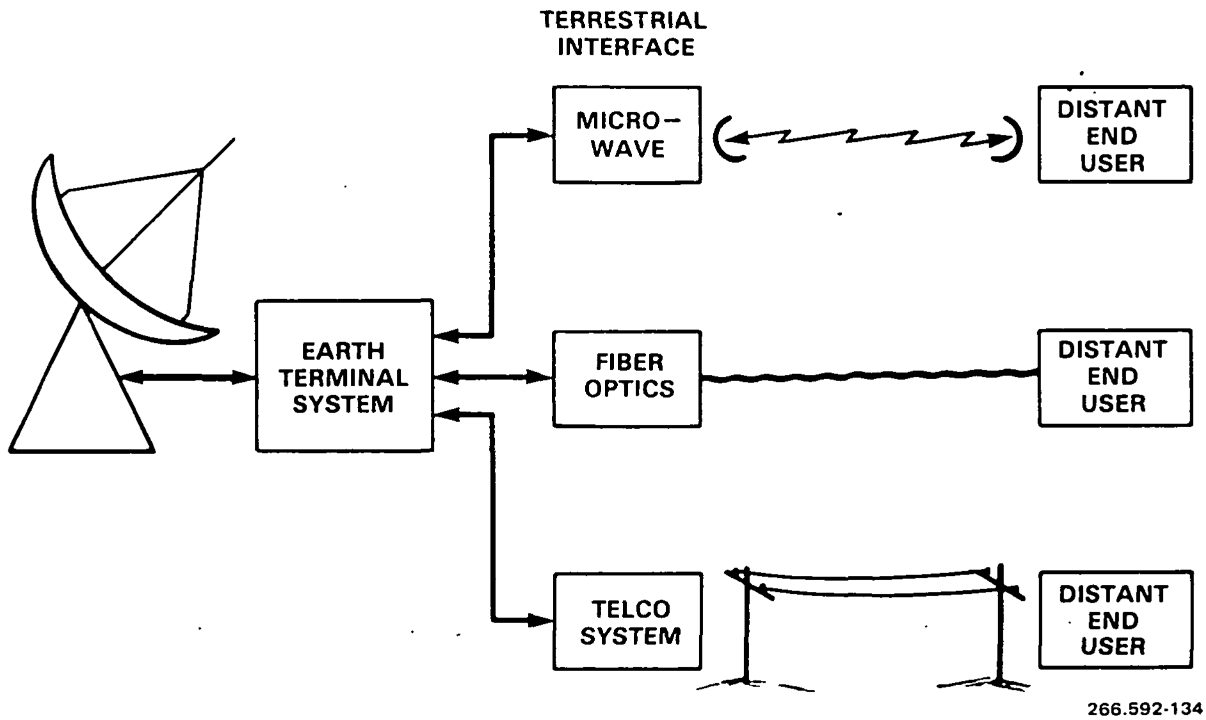

Figure 3-24. Terrestrial Data Distribution Options

system. One suggestion that has been made is use of a separate nearby dedicated communication satellite since this would probably reduce the number of antennas required due to space station geometrical antenna blockage.

c. Data Security. Encryption is probably required for most military application of the space station. Commercial users may require that their data be protected from competitors. Even with nonmilitary R&D missions it seems likely that over the lifetime of the space station there will be data that the U.S. will choose not to make available to foreign governments. Total security requirements must be studied to define the degree of security required - from simple PN encoding with restricted access to the codes up to use of military encryption boxes.

d. Intra-Platform Communication. The architecture of the intra-platform communication system must be selected. Since distributed processing has been chosen for the data management subsystem, the communication subsystem will be semi-autonomous. Much of the communications related computation will be performed by a dedicated C&T processor. The video and audio systems must be defined. One major consideration is the extent to which fiber optics will be utilized.

e. Interference Protection. The level of antijam protection to be utilized by the space station must be investigated. Both unintentional and deliberate S-band and K-band interference must be defined and method developed to protect against this interference. Null steering adaptive antennas and spread-spectrum are two candidate methods that may be used.

f. Flux Density Requirements. International regulations limit the RF power density from a spacecraft that impinges on the surface of the earth. The TDRSS recognizes this requirement and provides for the use of PN spread-spectrum to conform to the flux density limits at S-band. These limits vary from -154 dBW/4 kHz/m^2 for ground elevation angles of 5 degrees or less to -144 dBW/4 kHz/m^2 for angles greater than 25 degrees. We must determine which of the space station links must conform to this requirement. Can shuttle, OTV, TMS free flyers and the EVA links be considered as "occasional" happenings and as such exempt? Spread spectrum modulation requires the use of correlation receivers that take time to lock-up initially and after dropouts. This question must be answered before detail design of the communication system can be started.

3.2.4.1.4 Selected approach

a. Link Selection. The need for 9 external communication links was discussed earlier. Frequency band assignments have been made for each of these links and are presented in Table 3-13.

1. Ground via TDRSS. The 300 MBS downlink and 25 MBS uplink requirement will be satisfied using one KSA channel. Since one single access TDRS antenna has both an S-band and a K-band feed, one S-band channel may be utilized simultaneously to transmit up to 300 KBS of downlink and 12 MBS of uplink data. This would provide continuous communication in the event of a failure anywhere in the K-band system.

2. Ground via TDAS. This system, being totally TDRSS compatible, will use the Sand K-band links defined above. In addition, payloads up to 10 MBS will be accommodated on W-band (60 GHz) and very high data rate payloads will use the TDAS laser system.

3. Experiment Direct-to-Ground. Some payloads wish to transmit directly to ground. Accommodations for these payloads will be made on an individual basis.

4. Emergency-to-Ground. The purpose of this link is to provide communication in the event of a failure in the TDRSS/TDAS link due to equipment failure or failure of the platform guidance system. If the guidance system fails the platform may not know its altitude and be able to point the TDRSS/TDAS antenna beams at the satellites. For this reason the antennas for this system will be independent from the high gain phased array Sand K-band antennas. S-band has been selected as the primary frequency for this system due to the wide availability of ground stations. K-band will also be available.

5. Shuttle. The Orbiter Payload Interrogator (PLI) System is designed for use with other nearby vehicles and will be used as the primary communication link. It should be noted that the PLI system presently has a 16 KBS maximum limit on the data into the Orbiter and a 2 KBS maximum limit on the data out of the Orbiter. This system will have to be modified for the 48 KBS rates required for space station.

Table 3-13. Frequency Bands Used for Space Station Communication Links

Table 3-13. Frequency Bands Used for Space Station Communication Links

LINKS	GROUND				SHUTTLE	OTV/TMS	FREE FLYER	TETHERED SPACECRAFT	EVA
	VIA TDRSS PRE 1995	VIA TDAS POST 1995	EXPERIMENT DIRECT TO GROUND	EMERGENCY TO GROUND					
FORWARD LINK FROM SPACE STATION	S K_u	S K_u W LASER	EXPERIMENT DEPENDENT	S K_u	S	K_u	S	LIGHT	UHF
RETURN LINK TO SPACE STATION	S K_u	S K_u	NO REQMT.	S K_u	S	K_u	S	LIGHT	UHF

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6. OTV/TMS. Due to the possibility of a manned presence on the OTV or TMS and the consequently required video link, a K-band link has been selected.

7. Free Flyer. The low data rates required for this link are satisfied by S-band.

8. Tethered Spacecraft. There is no need for an RF spacecraft that is physically connected to the space station. A fiber optic transmission cable will connect the two spacecraft.

9. EVA. The UHF band has been selected for this link because a near-omnidirectional antenna system with minimum nulls is easier to attain at a lower frequency.

b. System Architecture. The overall architecture of the space station utilizes distributed processing for each major subsystem. The architecture of the communications subsystem (Figure 3-25) conforms to this philosophy and utilizes a Communications and Tracking System Processor (CTP). The CTP provides computations, control, data formatting and multiplexing, and is the interface with some experiments and with the space station main data bus. The Communications and Tracking System will have a dedicated data bus for control and data interchange between all system components. An operational memory is provided for storage of data that will be transmitted at a later time. Encrypters and decrypters are provided for use with data that is considered sensitive. A data compression subsystem is shown that would be used with high rate data from experiments that are amenable to data compression. The following transmitters, receivers and transponders are baselined for the system:

1. General Purpose S-Band Transmitter/Receiver. This will be used for communication with the Shuttle, OTVs, TMSs, ground stations and as a backup for other S-band transmitters and receivers. It will be able to handle up to 5 channels simultaneously. It will use the S-band antenna system which contains a number of multi-beam steerable phased array antennas capable of omnidirectional coverage.

2. TDRSS/TDAS S-Band Transponder. This unit will be used for transmissions to and from the relay satellites at S-band. It will also use the S-band antenna system.

3. General Purpose K-Band Transmitter/Receiver. This will be used for communication with other orbital vehicles such as Shuttle, OTV, TMS, other space stations, and with ground stations. It will be able to handle up to five channels simultaneously. It will use the K-band Antenna System which contains a number of multibeam steerable phased array antennas capable of providing omnidirectional coverage.

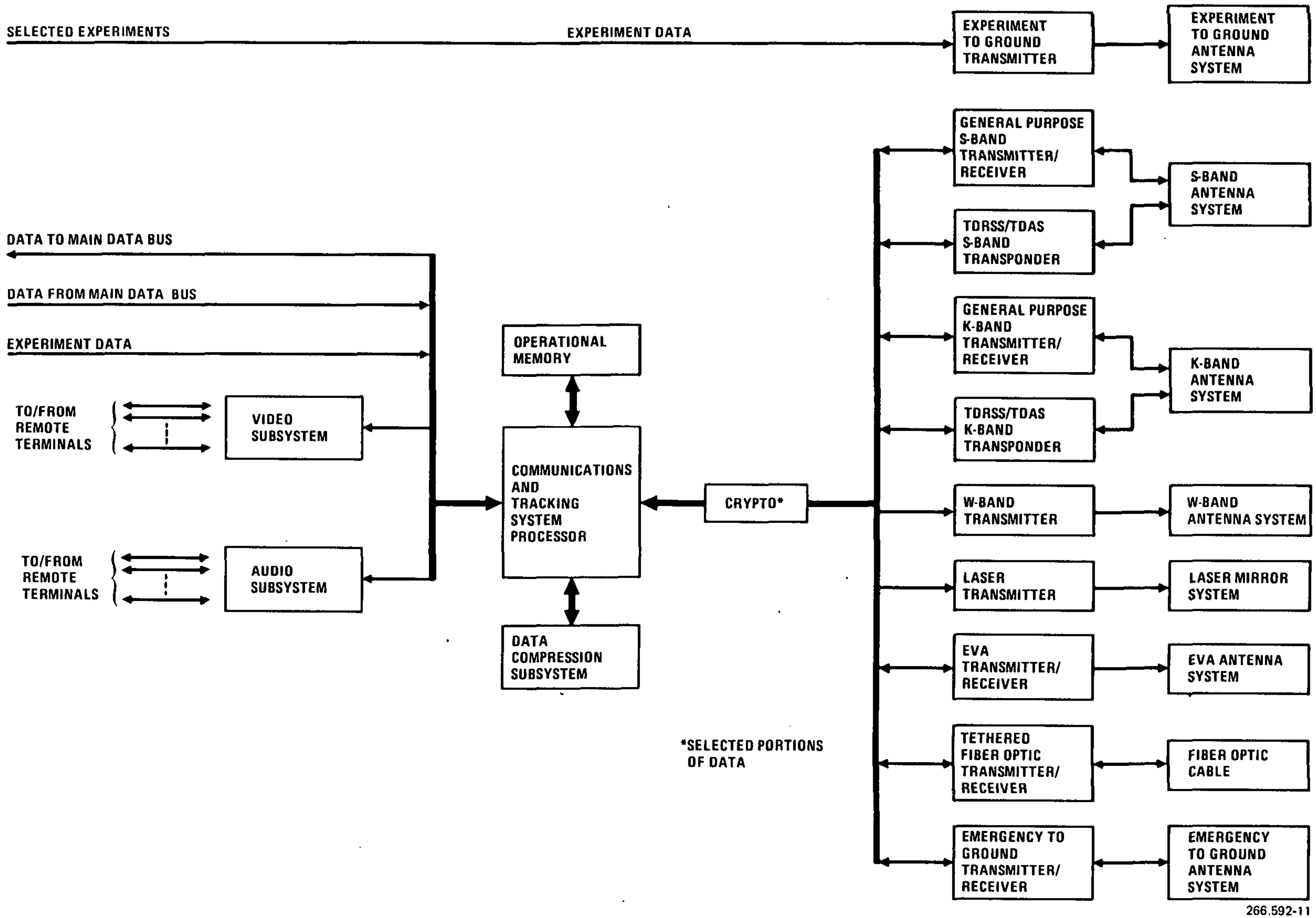


Figure 3-25. Space Station Communication System Architecture

4. TDRSS/TDAS K-Band Transmitter. This unit will be used for transmission to and from the relay satellites. It will use the K-band Antenna System.

5. W-Band Transmitter. This will be used for transmission of experiment data with a TDAS satellite.

6. Laser Transmitter. This will be used for transmission of very high rate data to a TDAS satellite.

7. Fiber Optic Transmitter/Receiver. This will be used for hard line communication with a tethered spacecraft. The receiver will be capable of reception of very high rate data.

8. EVA Transmitter/Receiver. This will operate in the UHF band and will be capable of duplex voice communication with two astronauts.

9. Emergency-to-Ground Transmitter/Receiver. This unit is S-band. It will have its own dedicated omnidirectional antenna system that will provide communication if space station altitude or position data is unavailable.

10. Experiment-to-Ground Transmitter. This transmitter and antenna will be installed for use with a particular payload that has a requirement for direct transmission of data to the ground.

The Communication System will be sufficiently autonomous such that it will operate if the Data Management subsystem fails. It will also contain provisions for emergency communications in the event of failure of the Space Station power system.

3.2.4.1.5 Technology needs. The following is a list of areas where ongoing R&D is necessary in order to support the timely development of a Space System program:

a. High Speed Multiplexers. The space station prime data link to ground will use the KSA service. One KSA channel will contain two quadraphase modulated signals of up to 150 MBS on each quadrature channel. The CTP must be capable of multiplexing several inputs into a 150 MBS bit stream. Present multiplexers do not approach this speed and intensive R&D is needed in this area.

b. Video Data Compression. Several proposed experiments have requested data at 3000 MBS which is not compatible with a single KSA channel when combined with 50 MBS of platform data. Research in data compression must be provided to reduce these large bandwidths if these experiments are to be flown in the preTDAS era.

c. Bit Storage. Storage of data is required in the preTDAS era for payloads that are operative in the TDRSS zone-of-exclusion. In excess of 10^{11} bits of storage may be required. This problem is discussed more fully in the Data Management section of this report.

d. Convolutional Decoding. Present TDRSS will accept rate 1/2 or 1/3 codes of constraint length 7 which yield system gains of approximately 5 dB. More sophisticated codes with longer constraint lengths will provide more gain if the decoding hardware is made available. This will result in reduced platform power requirements.

e. Beam Steering Algorithms. The S-band and K-band phased array antennas will track several targets simultaneously. Concurrently, null steering will be required to avoid intentional or unintentional RFI emissions. Work must be performed to provide the most efficient algorithms for beam steering.

f. Efficient Phased Array Antennas. The S-band and K-band phased array antennas may use distributed elements with individual transmit/receive modules at each element. DARPA has been working in this area which needs continuing developments.

g. Crypto Hardware. The need here is for encryptors and decryptors that will perform at the 150-300 MBS speeds that will be used by space station.

h. Fiber Optics Ground Distribution. Ground distribution of data via fiber optics has just begun. This is an option for distribution of data in the TDRSS era if the ground network is available.

i. TDAS Technologies. The critical technologies for TDAS development include W-band communications, laser communication links, development of a multi-beam K_a- or K_u-band antenna for distribution of data direct-to-users and development of an onboard NXM matrix routing switch. These items are included here to point out the space station need for the improved service of the TDAS.

3.2.4.2 Tracking

3.2.4.2.1 Overview. The tracking portion of the Communications and Tracking Subsystem has several RF links as shown in Figure 3-26. The following specific links have been identified:

a. Cooperative tracking of targets such as Shuttle, OTV, TMS, free flying satellites and possibly a second coorbiting space station.

b. Tracking of noncooperating and unknown objects.

c. Self tracking for orbit determinations through GPS and from unlinking of ground ephemeris data.

d. A docking system to provide accurate position and attitude data of vehicles that will dock and mate with the space station.

The technology required to support space station is not expected to be an obstacle in its development. GPS and TDRSS technology is nearing maturity. However, a search radar and docking sensor system will have to be developed for this project with technology that now, by and large, exists.

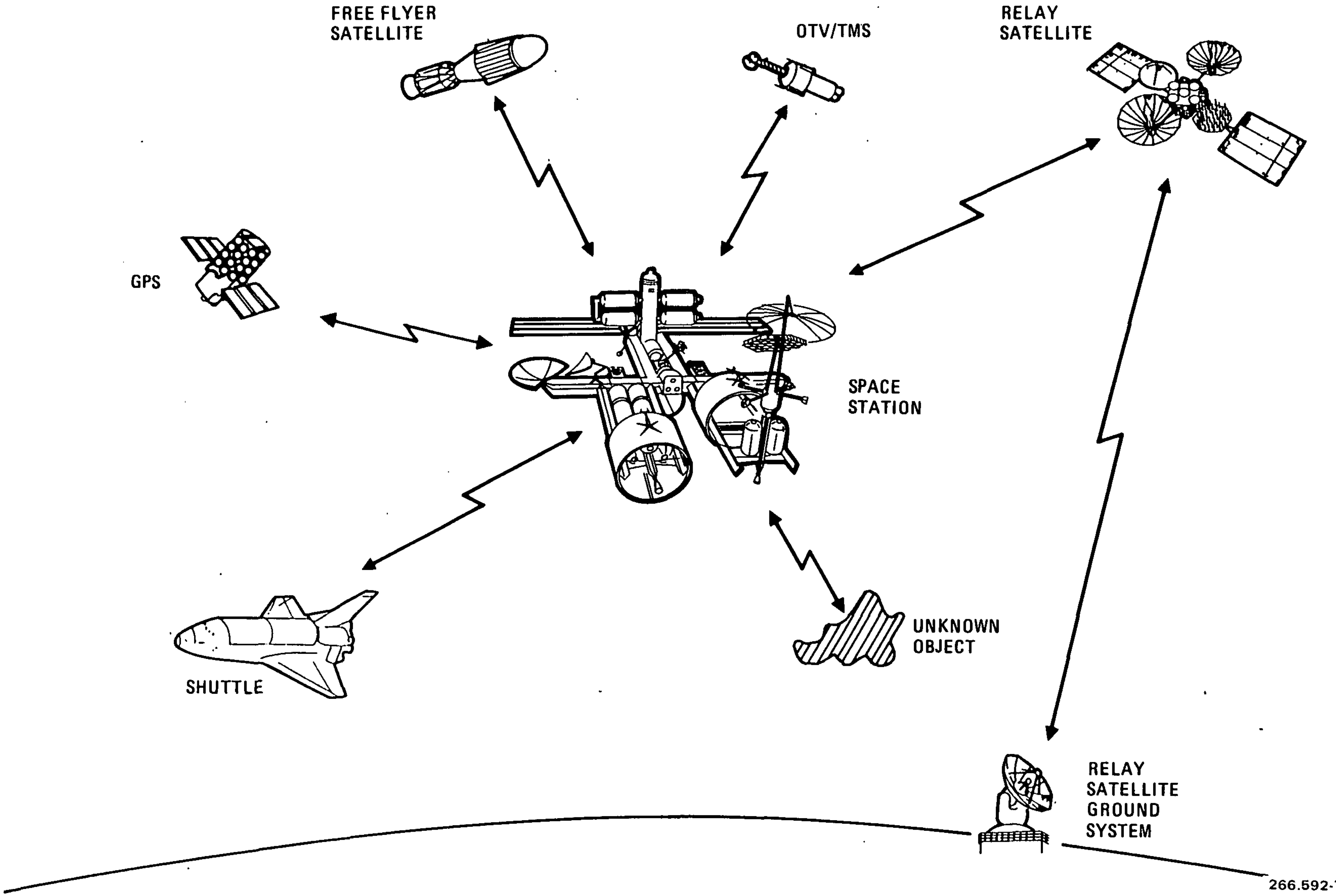


Figure 3-26. Space Station Tracking Links

3.2.4.2.2 Tracking system requirements

a. Surveillance Tracking Requirements. Tracking parameters for the various vehicles to be tracked have been identified (Table 3-14), although detailed values for these parameters were not defined during the course of this study. The surveillance tracking system must have the ability to simultaneously track up to perhaps 25 objects. A detailed analysis of the system requirement should be made during the next phase of this program.

b. Docking System Requirements. The docking system sensors will be required to provide relative position and attitude during docking maneuvers (Table 3-15). Maximum operating range of this system will be on the order of 100M. The accuracy and range parameters of this system cannot be determined until the requirements of the docking and latching mechanisms are defined. Based on previous studies, optical systems with multiple sources on the space station near each docking mechanism and small corner reflectors on the corresponding docking mechanism of the mating vehicle will provide more than adequate information.

c. Self-Tracking Requirements. No requirements for accuracy in the determination of the space station ephemeris have been made. It is assumed that the information available from the GPS, TDRSS and NORAD will be sufficient for space station requirements.

d. Antenna Coverage. The angular coverage requirements for the various links are given in Table 3-16. For self-tracking, utilizing GPS and TDRSS/TDAS, the requirements are dependent upon the space station mission stabilization requirements.

Table 3-14. Space Station Tracking Requirements

	VEHICLE TRACKED			
REQUIREMENT	SHUTTLE	OTV/TMS	FREE FLYER	UNKNOWN OBJECT
Range	*	*	*	*
Range Rate	*	*	*	*
Angle	*	*	*	*
Angular Rate	*	*	*	*
Cooperating Beacon	Yes	Yes	Yes	No
Angular Coverage	Omni	Omni	Omni	Omni

*Requirement exists but exact value not yet determined.

Table 3-15. Space Station Docking System Requirements

PARAMETER	REQUIREMENT
Max Range	100 M
Min Range	0
Range Accuracy	± 5 MM
Max Range Role	*
Min Range Role	*
Range Rate Accuracy	*
Relative Altitude Accuracy	*

*Requirement exists but exact value not yet determined.

Table 3-16. Tracking System Antenna Angular Coverage Requirements

SYSTEM	ANGULAR COVERAGE REQUIREMENT
GPS	Mission dependent. For earth stabilized missions, requirement is for coverage over slightly more than the upper hemisphere. For sun stabilized missions, omnidirectional coverage required.
Surveillance Radar	Omnidirectional
TDRSS/TDAS	Mission dependent. For earth stabilized missions, requirement is for coverage over slightly more than the upper hemisphere. For sun stabilized missions, omnidirectional coverage required.
Docking Sensors	Near-hemispherical coverage on the side of the space station with docking interface.

3.2.4.2.3 Options and trades. The purpose of this study is to define the Tracking System architecture. This has been accomplished. The following trade studies must be performed during the next phase of this study.

a. Surveillance Radar Definition. A detailed study must be made to define the requirements for this system. Range, velocity and radar cross section of all cooperating and noncooperating targets must be defined. The number of simultaneous targets must also be established. This data will be the basis for a trade study to select the space station surveillance Radar System. the frequency band is open at this time but Kor X-band are good candidates. Operating hardware is presently available at these frequencies and may possibly be adapted for space station use.

b. Docking System Definition. The requirements for the relative position and altitude of the space station and a docking vehicle must first be established. Some knowledge of the docking mechanisms and allowable closure velocities must first be established. Since tolerance probably will be on the order of millimeters and fractions of a degree, an optical sensor system would be a likely candidate.

c. Self Orbit Determination. No hard requirements are established at this time. It is assumed that the best available data from the GPS, TDRSS and NORAD systems will be adequate to satisfy program needs. If this assumption is not true, then the above information may be augmented with star seekers, horizon sensors and optical sighting techniques.

3.2.4.2.4 Selected approach

a. Link Selection. The frequency bands selected for the 4 links involved in vehicle tracking are shown in Table 3-17.

1. GPS. The GPS operates in the L-band. Space Station will utilize both the 1200 and the 1500 MHz allocations.

2. Surveillance Radar. At this point in time, before an in-depth surveillance tracking system study is performed, K_u-Band would appear to be the most promising choice with X-Band a second possibility.

3. TDRSS/TDAS. The frequencies to be used with these systems are S-band and K-band.

4. Docking Sensors. An optical system has been selected for the docking sensors.

b. System Architecture. The overall architecture of the space station uses distributed processing for each major subsystem. The architecture of the Tracking portion of the communications and Tracking subsystem (Figure 3-27) conforms to this philosophy and uses a Communications and Tracking System Processor (CTP). The CTP will receive data from the 4 tracking sensor systems and uses this data for antenna selection and pointing purposes. Position data is transmitted to other interested systems via the vehicle main data bus.

Table 3-17. Frequency Bands for Space Station Tracking Links

TRACKING SYSTEM	GPS	SURVEILLANCE RADAR	TDRS/TDAS	DOCKING SENSORS
Frequency Band	L-Band	Open - Probably K-Band	S-Band K-Band	Open - Probably Laser

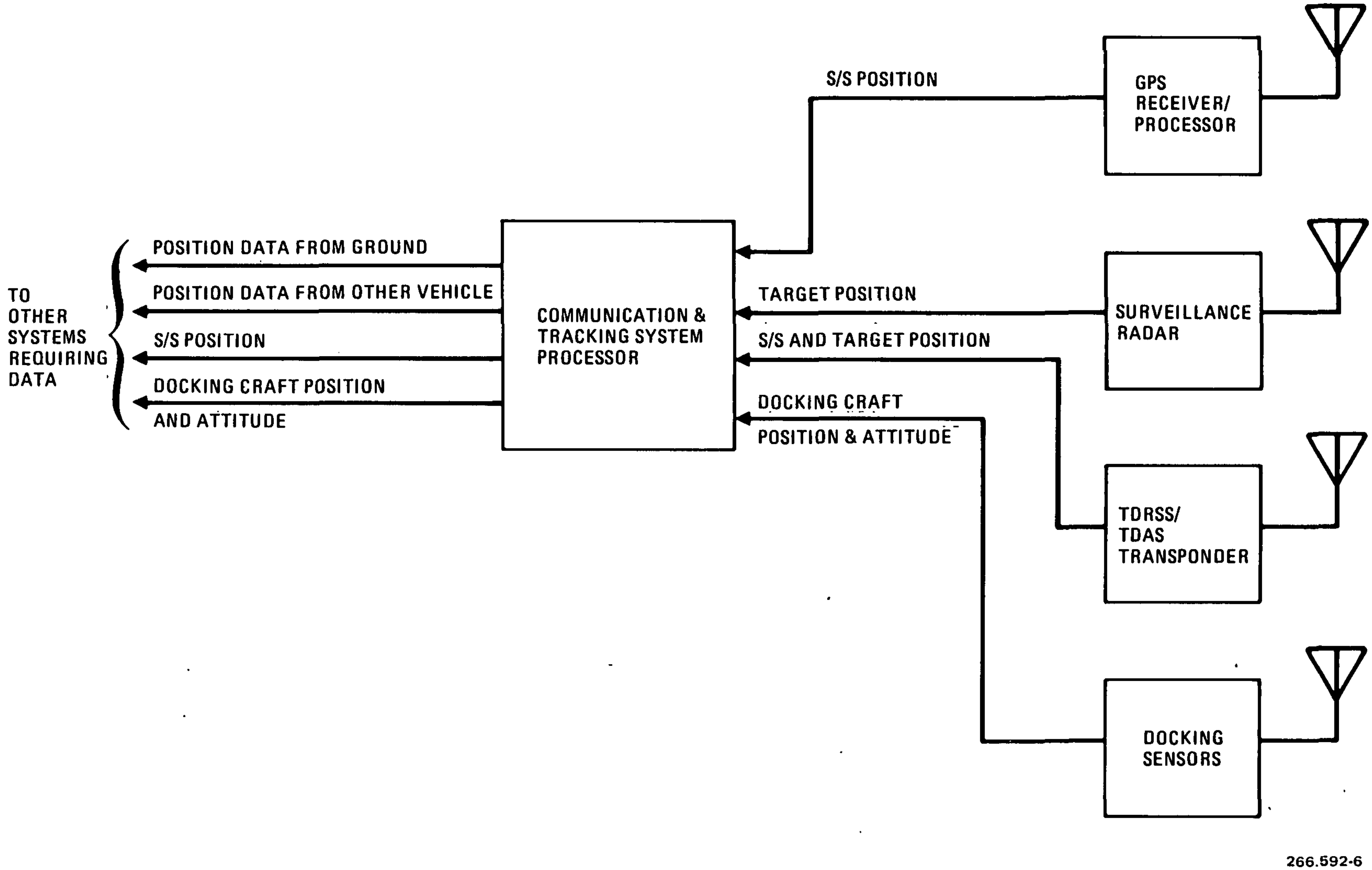


Figure 3-27. Tracking System Architecture

3.2.4.2.5 Technology Needs. No technology deficiencies are apparent that would prohibit the orderly development of the tracking and docking sensors necessary for the space station.

3.2.5 DATA MANAGEMENT. The data management study which was done for the space station is divided into four areas.

a. Computer architecture

b. Data storage devices

c. Radiation hardness

d. Fault tolerance

3.2.5.1 Computer Architecture. The computer architecture concept which is shown in Figure 3-28 is based on a distributed system which allows for higher computation speed and larger memory capacity which are not available in a centralized system. The distributed system provides easily integrated growth capabilities than that of other options available. Growth options

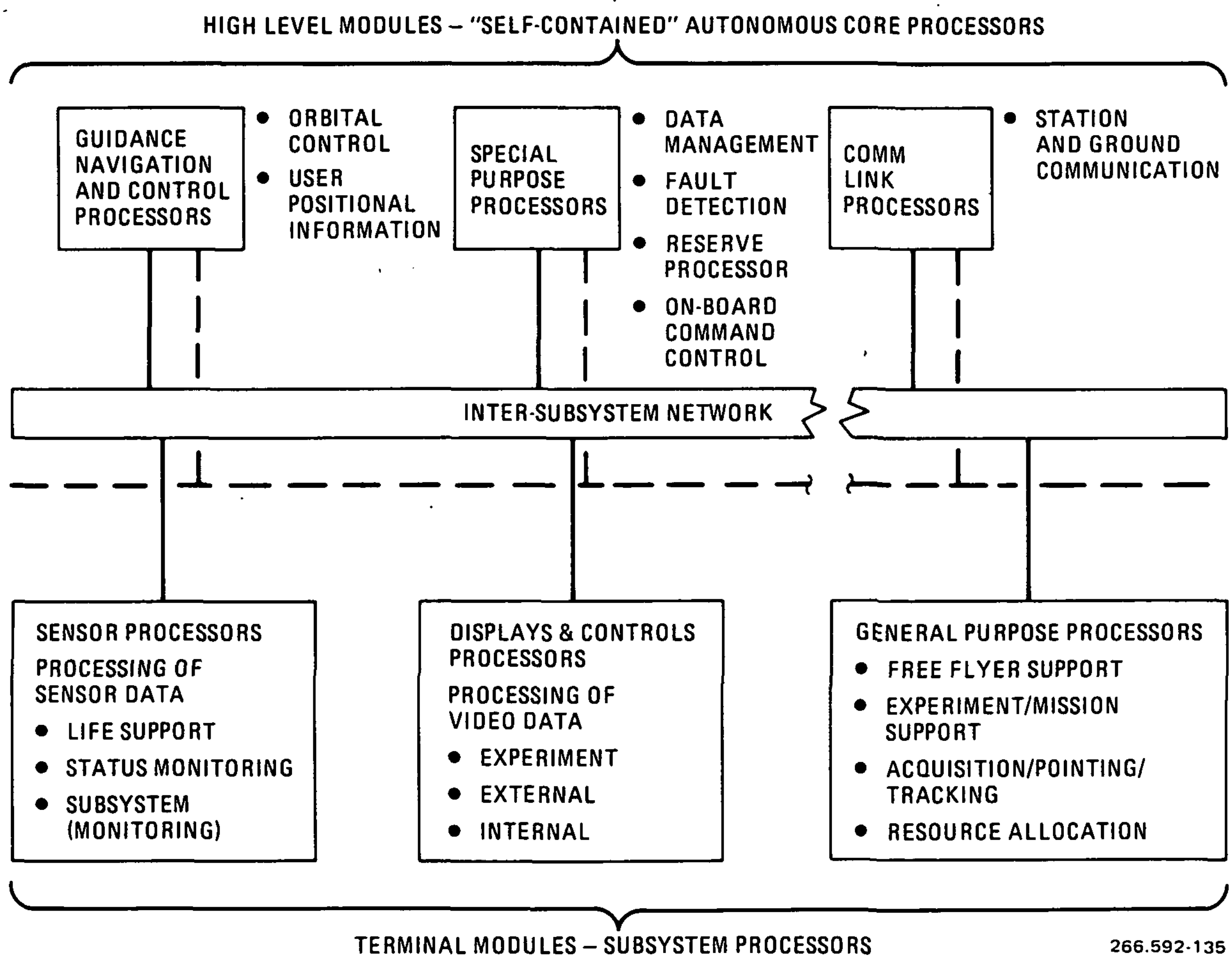


Figure 3-28. Computer Architecture

can be accomplished by either adding functions to an existing processor or by adding more processors.

3.2.5.1.1 Architectural considerations. There are several major considerations on which to base the choice of the computer architecture to use for space station:

a. A Loosely Coupled System is a set of highly autonomous subsystem elements connected by a common bus which can be used for subsystems intercommunication. These self-contained subsystem elements minimize integration problems as the subsystem grows or as additional subsystems are added. This loosely coupled system is assumed to be the basis of all subsystem element designs.

b. Subsystem Commonality allows interchangeability between hardware components which minimizes the development cost, technical risk and logistic support.

c. Standard Interfaces allow minimization of the proliferation of input-output devices.

d. Modularity would allow both unique configurations within components and minimum impact at the introduction of new technologies.

3.2.5.1.2 Architectural philosophy. A philosophy behind the architecture should be followed which considers the subsystem life cycle and the high cost of both change and repair. Consideration should also be given to the following:

a. Reliability (Subsystem, element and component)

b. Failure Modes

c. Radiation Hardness

d. Fault Tolerance

3.2.5.1.3 Architectural recommendation. Each subsystem element shown in Figure 3-28 generally contains several individual processors depending on the requirements of the functions to be performed. Redundant processors along with redundant data links may also be contained within the total subsystem to improve reliability. Data storage is part of each subsystem element with the option of memory expansion via the inter-system network.

The architecture can be divided into two levels of processor subsystems modules:

- High level modules -- Self-contained autonomous core function computer systems which are loosely coupled to a main bus.

- Terminal modules -- Subsystem processors which, depending on the function to be accomplished, could work autonomously or could work in conjunction with a high level module(s).

a. High Level Modules. Explanations of the functions of the subsystem elements within the high level modules are as follows:

1. Guidance and Navigation Control Processor Subsystem Element. This element would be responsible for orbital control, stabilization, orbital inclination, and could provide positional information to other processors.

2. Special Purpose Processor Subsystem Element. This element would be used for any or all of the following functions:

   (a) Data Management -- processor would allow control of a data storage unit adding expanded memory capability to the system.

   (b) On-board Command Control and Status Monitor

   (c) Automatic Fault Detection with backup processor selection

   (d) Reserve Processor -- for additional on-line processing capability

   (e) Subsystem Maintenance and Reconfiguration

   (f) Energy Management

   (g) Automation and Control Systems

3. Communication Link Processor Subsystem Element. All communication between station and ground control is via TDRSS and is handled by this element. This may be several processors with several dedicated channels for real time data processing and data storage needs and separate bus links for low speed data.

b. Terminal Modules. Explanations for the functions of the subsystem elements within the terminal modules are as follows:

1. Sensors Processor Subsystem Element. This element would process all sensor data such as life support, subsystem (experiment) monitoring, and space station status monitoring (includes energy monitoring). Depending on the function of the various processors in this element and communication requirements, separate dedicated bus interfaces with various high level modules or terminal modules may be required.

2. Displays and Controls Processor Subsystem Element. This element would contain computers which are required to process and distribute the various video data including experiment and internal/external video monitoring.

3. General Purpose Processor Subsystem Element. General Purpose Processors could be used for any subsystem element function not included in the other modules. These processors are generally

assigned tasks of a short term or transitory nature. Examples of some uses are as follows:

(a) Free flyer support

(b) Experiment/Mission Support

(c) Acquisition/Pointing/Tracking

(d) Resource Allocation

3.2.5.1.4 General purpose processor example. The actual physical interconnection of all processors will depend on their unique requirements. An example of how general purpose processors could be used for support of various experiments is shown in Figure 3-29. There are several methods of physical connection to these elements depending on the amount of data, the actual data rates, and the duration of the experiment. Embedded preprocessors may be required within certain experiments depending on the requirements of each individual experiment and the general purpose capabilities selected for space station. Experiments may then be grouped according to requirements. Examples of how each interface may be used are as follows:

a. Time Shared General Purpose Processor. The experiments or missions on this type of interface may each require a preprocessor per experiment due to the medium to high data rates and the amount of computation required. General purpose processors (GPP) may then be time shared, that is, one GPP may be on line to support several experiments.

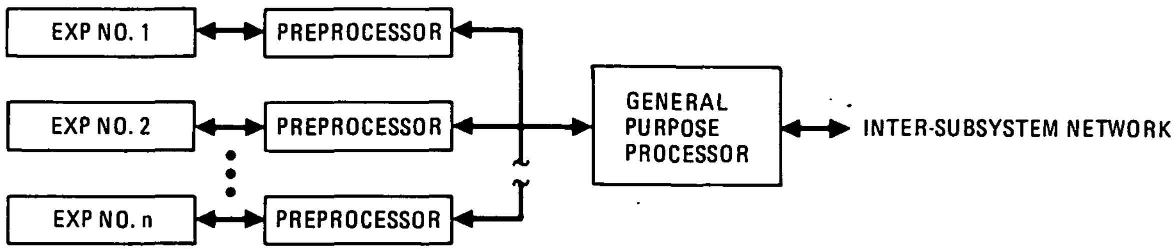
b. Time Shared Preprocessor. This type of interface would best be used with experiments or missions which had infrequent run times, low data rates and/or are on for short durations. A time shared nonembedded preprocessor directly linked to a GPP could then handle the computation and data rates involved.

c. Dedicated General Purpose Processor. For experiments or missions which have very high data rates with real time data requirements the dedicated interface could be used. This interface may also be suited to a system where a large amount of processing is required or the run-time per day is very long.

3.2.5.1.5 Inter-subsystem network. Depending on the functional requirements of the various processors, the capability of additional processing or memory allocation via the inter-subsystem network exists. This allows terminal modules such as the sensor or displays and controls to use a Special Purpose Processor. However, the inter-system network should be utilized for only short periods of time. This implies that each subsystem element be as self-contained as possible (maximum memory and processing capability feasible). Communication between elements therefore should only be required at peak periods of operation (noncritical) or for short time growth expansion of the total subsystem. Several separate buses are foreseen in the total subsystem for solution of real time data requirements or as dedicated links.

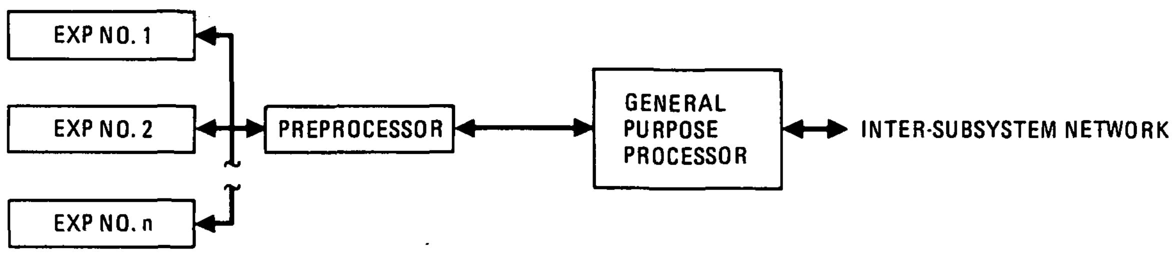
A redundant intersubsystem network eliminates the possibility of a single point failure inhibiting communication between various processor elements and should be considered.

TIME SHARED GENERAL PURPOSE PROCESSOR



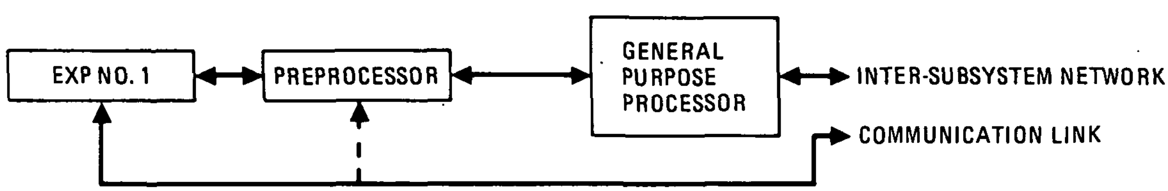
EXPERIMENTS ON THIS INTERFACE MAY EACH REQUIRE A PREPROCESSOR PER EXPERIMENT DUE TO THE MEDIUM TO HIGH DATA RATES AND THE AMOUNT OF COMPUTATION REQUIRED.

TIME SHARED PREPROCESSOR



THIS TYPE OF INTERFACE WOULD BEST BE USED WITH EXPERIMENTS WHICH HAD INFREQUENT RUN TIMES, LOW DATA RATES AND/OR ARE ON FOR SHORT DURATIONS.

DEDICATED GENERAL PURPOSE PROCESSOR



THIS INTERFACE WOULD BE USED FOR EXPERIMENTS WHICH HAVE VERY HIGH DATA RATES WITH REAL TIME DATA REQUIREMENTS WHICH CALL FOR THE USE OF A DEDICATED INTERFACE TO THE COMMUNICATION LINK.

266.592-136

Figure 3-29. Experiment Interfaces

The requirements of the various interfaces will determine the actual type of interconnections needed. Several evaluations of various bus media, connection methods and protocols need to be made. Each evaluation should be made with respect to:

a. Failure modes

b. Radiation hardness

c. Speed

d. Power

e. Reliability

f. Weight

g. Cost

h. Ease of expansion

For the data rates involved, a viable bus option is fiber optics. This type of bus has a high immunity to electromagnetic interference, has a broad bandwidth (up to several hundred MHz, some fibers GHz) and excellent data security. Also the fiber optics' size and weight lends itself well to space station physical constraints.

The actual physical links used on space station will probably be a combination of physical bus types (fiber optics, coaxial, twisted pair). Again the requirements will determine which type will be used and where.

3.2.5.2 Data Storage Devices. There are several types of data storage devices and concepts available. The specific type of memory chosen for data storage on space station should be dependent on the function required. Table 3-18 lists several types of memory devices, where they should be used and the advantages of that technology.

Figure 3-30 shows an example of the memory interfaces which could be implemented in an embedded processor.

There are new technologies in data storage devices which are candidates for future space station applications. A discussion of three of these technologies and their features and disadvantages follows:

a. Bubble Memory. This type of memory technology provides highly reliable mass data storage because of its nonvolatile nature in a radiation environment. At the present time, bubble memory devices have a memory capacity of 1M bit/device.

   Problems associated with the bubble memories are the slow read/write cycles, limited temperature range, and the high power requirements. Other problems with this type of memory include a slow transfer rate (200 KBS) and bit error rate problems due to bubble migration.

b. Optical Disk. Optical disks provide a very high bit density on disk with a much greater resolution than that of magnetic tape. Applications where this data storage has the most advantages is where data turnover is low

Table 3-18. Data Storage Devices

Memory Type	Where Used	Advantages
RAM (Random Access Memory)	Data and Signal Processing	This read/write memory would be used where any temporary storage is needed. Other benefits are the high bit densities per device, and they are radiation hardened.
Nonvolatile RAM (CORE memory)	Temporary Data Storage	Allows memory space for frequently updated data. Other advantages include high bit-densities on chip, relatively low read/write power, and retains memory content after a power loss.
Sequentially Accessed Memory (Magnetic Tape, Bubble Memory)	Mass Memory Data or Data Buffers	This memory has both a relatively low dollar per bit cost and it allows for power down without memory loss.
CMOS; CMOS/SOS (complementary metal oxide semiconductor; CMOS/Silicon-on-Sapphire	Data Processing and portions of Signal Processing	These memory types are both low power and radiatian hard.
Bipolar	Signal Processing	Bipolar memories have very short access time, therefore, they are very high speed devices.

and/or data security is crucial. Today's optical disk technology has a 10G byte capacity with less than 100 millisecond access time, and densities of about 10^8 bits/cm^2.

Because the optical disk is now based on permanent deformation of the medium, its major disadvantage is its write-once limitation. Future advances may allow multiple writes.

c. High Density Digital Magnetic Tape Recorder (HDDR). This recorder has become a successful method for achieving both large storage capacity and very high data rates. Digital electronics may also be installed which allow either a serial-in/serial-out or parallel-in/parallel-out operation. This field is still growing and at the present time the HDDRs have a bandwidth limitation of 8MBPS/track. A typical one inch wide tape, 42 track system uses two tracks for time code and housekeeping, four tracks for error correction and 36 tracks for digital data. The 20 percent overhead allows for 240MBPS as the maximum data rate.

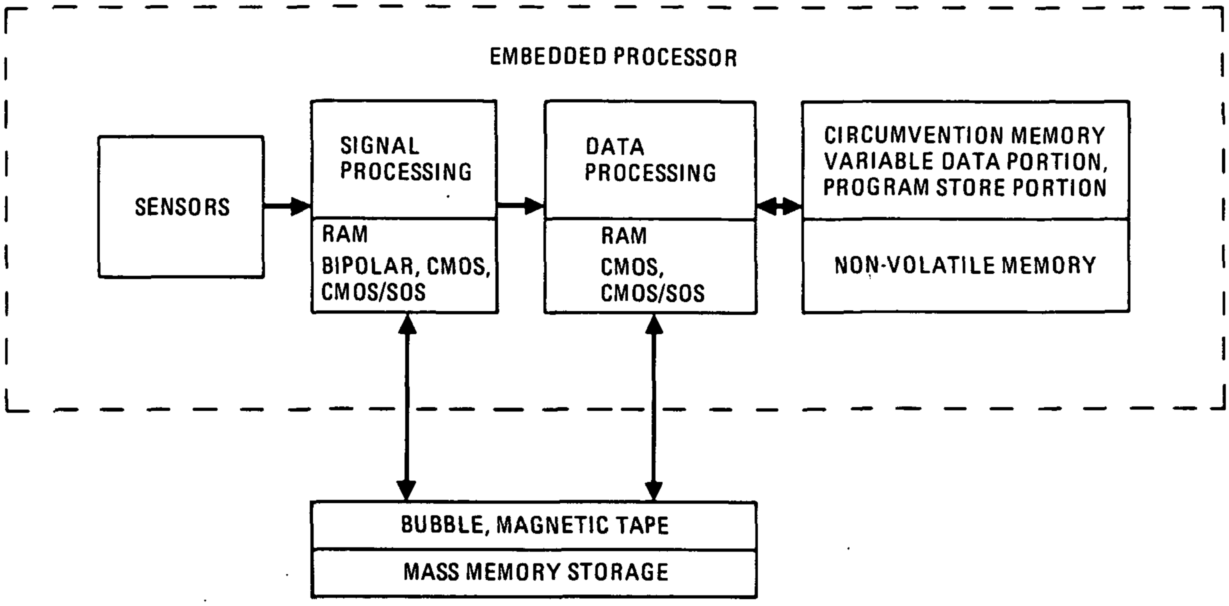


Figure 3-30. Typical Memory Applications

The space station requires recording data at a rate greater than 240M BPS during certain earth observation experiments. However, with HDDR technology there are other methods to allow even higher data rates:

- Two 42 track systems in parallel

  Disadvantages: a) initial hardware cost
  b) head replacement cost
  c) tape control problems

- Use wider tape

  Disadvantages: a) tape cost
  b) development cost
  c) head replacement cost

- Recommended Method

  Use of a 52 track head and a one inch wide tape on a 14 inch reel. This combination would allow 300MBPS to be recorded for 7.5 minutes.

3.2.5.3 Radiation Hardness. The main objective in designing radiation-hardened processors is to identify electronic devices that can survive in specified environments, including that of natural radiation in space for specified times. This technology is growing and should be maturing in the next few years. Another criteria in choosing devices is that they must be compatible with emerging programs and future system concepts.

Electronic components reaction to radiation environments depend on the circumstances of exposure. Generally, in space the dose rate is a few RADs per day. In certain zones (Van Allen Belt) the rate is 24 RADs per day. Additionally, a nuclear event can produce millions of RADs per second for a very short period of time.

Other considerations of radiation protection should be the DoD requirements and the lifetime requirements of all electronic devices and equipment.

There are four major areas of concern to electronic designers with respect to radiation in space:

a. Cosmic Rays

b. Solar Radiation

c. Van Allen Belt

d. Nuclear Event Radiation

Electronic components can receive either permanent damage or transient effects from radiation exposure. Permanent damage is defined as a reduction in performance of a device to a level from which it cannot recover. Transient effects are only temporary disruptions to normal operation. (A device would then recover after the disappearance of the environment which caused the disruption.)

3.2.5.3.1 Radiation effects reduction methods. Since the amount and type of radiation differ in different altitudes and inclinations in space, different reduction techniques must be considered for each orbit.

The following is a list of methods by which a designer could minimize radiation effects:

a. Radiation Hardened Devices

b. Circumvention Circuitry

c. Magnetic Memory

d. Circuit Design Techniques

e. Shielding (substantial shielding may not be satisfactory in space systems because of the weight)

Table 3-19 presents the long term goals for three types of integrated circuit technology.

The electronic circuits should be designed for degradation by using conservative designs and worst case analysis. The worst case analysis may be based on the neutron density and total dose rate, low temperature conditions, and worst initial conditions.

Table 3-19. Long-Term Goals for Three Types of Integrated Circuit Technology

BULK CMOS	
Total Dose:	Goal: 10^6 rad (Si)
Dose Rate:	No Upset: 5×10^8 rad (Si)/sec
	Survive: 10^{12} rad/sec
GALLIUM ARSENIDE (GaAs)	
Neutron:	5×10^{15} N/cm^2
Total Dose:	1×10^8 rad (GaAs)
Dose Rate:	Upset: 5×10^{10} rad (GaAs)/sec
	Survive: 5×10^{11} rad (GaAs)/sec
BIPOLAR	
Neutron:	3×10^{14} N/cm^2
Total Dose:	10^{16} rad (Si)
Dose Rate:	Upset: 5×10^8 rad (Si)/sec
	Survive: 10^{12} rad (Si)/sec

3.2.5.4 Fault Tolerance. Another major data management consideration is space station reliability. To be reliable a fault tolerant computer system must possess the capability to execute a set of programs correctly in the presence of certain specified faults including hardware failures and software errors.

3.2.5.4.1 Fault tolerance requirements. The following criteria and subsystem requirements must be evaluated in developing the requirements for a fault tolerant computer system:

a. Detect, identify, and recover from system faults

b. Continuous operation in the absence of ground control

c. Reconfigurable system which could reconfigure in response to failure conditions

3.2.5.4.2 Protective redundancy. Fault tolerance includes the use of protective redundancy which must be balanced between total subsystem cost and reliability. Protective redundancy includes the following:

a. Hardware replication

b. Error correcting code

c. Software replication

3.2.5.4.3 Hardware/software redundancy. Redundancy does not attempt to prevent the occurrence of faults but rather to provide the means for the processors to continue to operate usefully after certain faults have occurred.

The main areas in which fault tolerance should be applied are as follows:

a. Software

   -- Partitioning of functions

   -- Functional redundancy of software elements

   -- Self-checking techniques

   -- Support of real-time changes

b. Hardware

   -- Partitioning of functions

   -- Self checking for support of isolation and recovery

The future for fault tolerance in computer systems involves the use of artificial intelligence with hardware support (probably available by 1995). Today the level of fault tolerance used must be based on the reliability and survivability required weighed against actual total cost of subsystem redundancy and protection.

Recommendations and Conclusions

Several areas discovered in the course of the data management study which need more research are as follows:

- Processor/Data storage

  -- Requirements for processor hardware based on speed, memory, power, weight, modularity, standard interfaces, redundancy, environmental, logistics, maintenance and reliability concerns must be studied and addressed. The use of common requirements will assure minimum schedule risks and technical risks when dealing with multiple vendors and easy integration as the space station matures.

  -- Data storage requirements must be analyzed and defined based on space station growth.

- Requirements of experiments/missions

  -- Priority of data

     1. Real time data

     2. Noncritical data (preprocessed)

  -- Amount of data to be stored

- Software Requirements

  -- The software required for space station is a separate issue in its own right. An individual study is needed to develop the requirements. We realize its importance but elected to not study that issue at this time.

- Computer Network

  -- Studies in bus architecture are attracting a large amount of interest from commercial industry. Results of these studies and any standards which are derived should be selected for application on space station. Additionally, total system networks (ground stations, space stations, free flyers, communication satellites) must be analyzed to arrive at the most efficient architecture and an optimum protocol.

- Data Compression Techniques

  -- Any application in which data can be preprocessed should be noted and techniques for compression of the data should be studied.

The technical growth aspect of space station requires the development of a loosely coupled modular computer system which allows for easy integration of additional or upgraded peripherals. The initial system architecture created should therefore reflect this need for technical growth potential.

3.2.6 CREW AND LIFE SUPPORT. The Crew and Life Support provisions of a Space Station will include those subsystems and equipment necessary to sustain life, maintain health, ensure safety, and provide livable, comfortable surroundings. In describing how a Space Station might achieve these goals, this study has attempted to consider man's future role in space as indicated by the needs survey and user requirements of Section 1, the results of past manned missions, conclusions of previous studies, established physiological and human engineering standards and guidelines, technology availability, and cost.

3.2.6.1 Requirements. The requirements for crew and life support are discussed below. Other requirements having major impact on this area such as mission duration and complexity, orbit and inclination, crew size, mix, and organization, work/rest cycles, and off duty activities, are discussed earlier (Sections 1 and 2).

3.2.6.1.1 Internal environment. The interior pressurized volume of a manned Space Station must provide atmosphere, thermal control, and radiation protection to support the crew and live specimens in the payload. In addition, it must provide an acoustic and lighting environment which is comfortable and enables productive work, and it must provide safety factors and allowances for contingencies appropriate to the mission parameters. Environmental safety requirements are discussed in paragraph 3.2.6.1.11.

a. Atmosphere. The atmosphere of a manned Space Station must provide oxygen, carbon dioxide removal, trace contaminant and odor removal, control of particulates and microbial count, temperature and humidity control, and air circulation. The total atmospheric pressure selected for the station determines the amount of diluent gas needed. For safety, reliability, and payload requirement considerations, a total pressure of 14.7 psia is recommended, with 20-22 percent oxygen during normal operations, and 78-80 percent nitrogen. Other atmospheric requirements are listed in Table 3-20 below.

In addition to the requirements above for crew atmosphere, the animals and plants in the payload will require an isolated atmosphere with, in some cases, more stringent requirements imposed by the scientific investigation, in which they are subjects. Furthermore, crew health and safety dictates bioisolation of the animal atmosphere. This will require separate removal of carbon dioxide, trace contaminants, odor, particulates, and microbial species from the atmospheric effluent of the animal and plant research lab.

b. Thermal Control. The station will provide a heat rejection capability to provide for crew metabolic heat loads under nominal (467 BTU/man/hr) levels of activity, and also for electronic and other heat producing subsystems, so as to maintain environmental temperature limits as specified above.

c. Radiation. The Space Station shall provide shielding which, when coupled with appropriate procedural safeguards and personal protection, shall be capable of limiting a career space crew's exposure to the limits listed in Table 3-21.

Table 3-20. Operational Requirements for Atmosphere Control

Total Pressure	14.7 psia
O_2 Partial Pressure	2.9-3.2 psia (20-22 percent)
N_2 Partial Pressure	11.8-11.5 psia (80-78 percent)
CO_2 Partial Pressure	less than 3.8 mmHg
Temperature	65-80F adjustable
Humidity	40-70% Relative Humidity
Airflow	15-40 ft/min adjustable
Particulates	50 micron max
Microbial Count	less than $100/ft^3$
Trace Contaminants	24 hr standard per ACGIH
Odor	removal (subjectively acceptable levels)

Table 3-21. Radiation Exposure Limits and Exposure Rate Constraints for Unit Reference Risk

Exposure	Bone Marrow (5 cm)	Dose in REM Skin (0.1 mm)	Eye (3 mm)	Testes[2]
1 yr avg daily rate	0.2	0.6	0.3	0.1
30-day maximum	25	75	37	13
Quarterly maximum[1]	35	105	52	18
Yearly maximum	75	225	112	38
Career limit	400	1200	600	200

1. May be allowed for two consecutive quarters followed by six months of restriction from further exposure to maintain yearly limit.
2. These dose and dose rate limits are applicable only where the possibility of oligospermia and temporary infertility are to be avoided. For most manned Space Station missions, the allowable exposure accumulation to the Germinal Epithelium (3 cm) will be the subject of a risk/gain decision for the particular mission and individuals concerned.

Radiation hazard is dependent on altitude and orbital inclination. The natural radiation environment is more severe in geosynchronous orbit (GEO) than in low Earth orbit (LEO), and is highly variable with time of day and geomagnetic activity. For operations in near-equatorial or 28.5-degree orbits solar flares pose no hazard but must be guarded against for operations at GEO and in higher inclination LEO orbits that would be considered for dedicated military space station operations. Van Allen radiation hazards are dependent on orbital track in LEO orbits, since the Inner Belt dips close to Earth over the South Atlantic (centered at 35 degrees west, 35 degrees south) forming the South Atlantic Anomaly (SAA). A vehicle in a 28.5-degre orbit flying between 400 and 500 km altitude would miss the highest energy portion of SAA for approximately 18 of each 24 hours. Therefore, shielding in a 28.5-degree LEO station of approximately one gm/cm^2 should be provided by the station structure, and EVA should be scheduled within the "safe" 18 hours of each day.

The Outer Belt dips close to the Earth in the region of both magnetic poles. A station in high inclination LEO orbit would be irradiated in the vicinity of the poles. However, irradiation is limited to discrete portions of the LEO orbit, either the poles or the SAA or both, depending on inclination, and pose no hazard outside those portions. Whereas low-inclination tracks pass through the SAA, they miss the "polar horns" entirely; most 55-degree inclination tracks pass through the polar horns 1-4 times per revolution, but avoid the SAA. As altitude increases, the level of radiation in each portion increases.

Therefore, when the time comes that user requirements and budget enable the establishment of a high inclination or polar LEO station, a safe-haven will be required providing 4-6 gm/cm^2 and severe time restrictions or personal shielding, for EVA; a GEO station would require a safe-haven with a wall mass of approximately 20 gm/cm^2 to reduce the average dose expected from the 5 to 9 solar flares per year to within allowable limits.

In addition to the natural radiation environment, doses from payload and operational sources, both ionizing and nonionizing, must be considered. The limits of Table 3-21 will apply to internal sources exposure, as well as the electromagnetic radiation limits specified by ACGIH (Reference NASA Reference Publication 1045).

d. Acoustics. The station will be designed to limit the crewmembers' noise and vibration exposure to provide a comfortable environment for nominal conditions and a safe environment during those intermittent operations which necessitate exceeding nominal levels. The background continuous noise level at the ear should not exceed 55 dBA, and in no case should interfere with speech intelligibility. Continuous vibration should not exceed 0.48 m/sec^2 at 0-4 Hz or 0.15 m/sec^2 at 8-16 Hz. The sound pressure level for ultrasonic noise should not exceed 75 dB in 1/3-octave bands centered at 8 to 16 kHz or 110 dB at 20 to 31.5 kHz. Brief exposures to low frequency noise shall be limited according to criteria in NASA SP-3006 (Bioastronatics Data Book), and other work-day noise exposures of a few minutes to 8 hour durations shall be limited according to criteria of the Occupational Health and Safety Act, 1970.

e. Lighting. General illumination, visual displays, work station lighting, shadows and glare, brightness ratios, and contrast shall be provided in accordance with MIL-STD-1472B and MSFC STD 512A. The station's habitat shall have adjustable lighting levels in both common areas and private quarters.

3.2.6.1.2 Architecture. The Space Station shall provide functional elements to accommodate payload requirements and to accommodate the crew which operates those payloads. Consideration is given to volume, orientation, traffic patterns, stowage, access/egress, crewmember privacy, and other factors, in order to maximize crew performance and productivity. Architectural safety requirements are addressed in paragraph 3.2.6.1.11.

a. Interior Volume. The Space Station shall provide a pressurized volume to accommodate the number of crew members given in subsections 2.2.6 and 2.2.9 and the man-operated payloads of subsection 4.1.3. Considering each crew's stay time in orbit to be 90 days or longer, a high value is placed on providing more than "minimum adequate" volume for living quarters. Volumes required for the various functions are listed in Table 3-22, assuming an early years crew of 5 and later years crew of 12.

Regarding the habitat function, the 120 m^3 of habitable volume should provide 25 m^3 as private quarters for a crew of five, or 5 m^3 (180 ft^3) per man. Depending on the configuration, a passageway of 26 m^3 (early years) to 52 m^3 (later years) may be required.

Table 3-22. Manned Volume Requirements

	Early Years		Later Years	
	Pressurized	Habitable	Pressurized	Habitable
	Volume, $ft^3(m^3)$	Volume, $ft^3(m^3)$	Volume, $ft^3(m^3)$	Volume, $ft^3(m^3)$
Habitat	6,400 (180)	4,224 (120)	12,800 (360)	8,448 (240)
Station Ops	4,224 (120)	2,836 (80)	4,224 (120)	2,836 (80)
Missions	12,800 (360)	8,448 (240)	32,000 (900)	21,333 (600)
EVA Airlock	150 (4.2)	140 (4.0)	300 (8.4)	280 (8.0)

In addition, a logistics resupply function would be part of the pressurized volume over and above that listed in Table 3-22. A module performing this function should be sized for early years' growth expectations, so as not to require a second module, thus, accommodating 7-8 crewmembers for 90 days. The module should accommodate approximately 720 man-days supply of the following:

	ft^3
Food	260
Water	238
Personal Gear	100
ECLSS Expendables	90
EVA Resupply	105
Hydrazine	245
Maintenance & Housekeeping Supplies	70
Station Spares	50
Trash Return (Compacted)	274
Waste Compartment	70
TOTAL	1,502 ($46m^3$)

Therefore, a logistics module would need to include approximtely 2,000 ft^3 (62 m^3) of pressurized volume, allowing 500 ft^3 for manned access.

b. Orientation. The local vertical shall be consistent throughout a module, and the elements of the station in which the most crew activity takes place, i.e., the habitat, the station operations area, and the mission areas, shall each use the same vertical relative to their common geometry.

Thus, if cylindrical modules are used, each of these functions will use a radial or axial vertical. For reasons of commonality with Spacelab hardware relating to cost and payload compatibility, a radial vertical (each module floor parallel to the long axis of the cylinder) is specified here.

Artificial gravity for crew support is not recommended for 90-day missions in the 1990-2000 time frame. This issue is discussed later in Paragraph 3.2.6.2. Part of the Life Sciences payload will require artificial-g at various levels between 0.1g to 1-g. This will be accommodated by a centrifuge in the Animal and Plant Research Lab.

c. Privacy Provisions. The station will provide separate sleep/study quarters for each crewmember, and provide for privacy in personal hygiene functions, accommodating both males and females. Each private quarter will have a sleep station, desk, and approximately 20 ft^3 of personal stowage. These quarters will be insulated from one another and the station such that light and the intermittent noise of normal station operations is attenuated to levels conducive to sleep. In addition, the private quarters shall provide adjustable airflow, an intercom, personal audio equipment, a personal computer, selectable colors and decorations, adjustable illumination, and an observation window. Plants are permitted but not required in the private quarters.

d. Traffic Patterns. The Station shall be designed so as to minimize traffic past private quarters and work stations. Except for food operations, routine housekeeping, inflight maintenance, and medical activities, no mission work will be required by design to be performed in the habitat. A central corridor concept shall be used to facilitate rapid translation through an element of the Station.

e. Access and Egress. There shall be at least two means of access/egress from each manned module. There shall be a minimum of one primary and one secondary access/egress route between habitat modules and between a habitat module and the safe-haven (see Safety, Subsection 3.2.6.1.11). The two routes to safe-haven shall not require EVA. Other modules' second access may be via EVA.

A primary access route shall have an internal cross section of 5.5 feet in its smallest dimension, or room for two EVA suited crewmen to pass at the same time. A secondary access route shall have an internal cross section of 3.5 feet in its smallest dimension, or room for two shirtsleeved crewmen to pass at the same time. The station shall be designed such that a crewmember can get from any manned element of the station to the safe-haven within 90 seconds.

f. Stowage and Retrieval. The logistics element of the station shall serve as a major source of stowage volume (see Paragraph 3.2.6.1.2.a). From this element some supplies will be transferred to other locations in the station to permit stowage near place of usage. For example, clothing and personal gear will be stowed in private quarters and a one-week supply of food will be stowed in the habitat. Items to be restowed will be loaded with a moderate packing factor for ease of restowage. Emergency medical equipment, e.g., cardiac resuscitation equipment, shall be readily accessible in both the habitat modules and the safe-haven.

In addition to the logistics module, there shall be maintained a 150 man-day supply of life supporting logistics in a safe-haven.

g. Observation Windows. There shall be one observation window near each EVA airlock, one in the main dining area, and one in each crewmember's private quarters. No observation window or optical quality requirements were identified by Science and Application payloads in this study.

h. Colors and Textures. The station shall provide for individual changeout of wall color and texture in private quarters. A variety of textures shall be used throughout the station considering acoustic, mobility, and safety requirements. Color choices for common areas and work areas shall be based on generally accepted principles of interior and spacecraft design.

3.2.6.1.3 Locomotion and restraints.

a. Locomotion Aids. The station shall provide handholds and footholds along each interior avenue of traffic. In addition, "friction surfaces" shall be selectively placed along avenues of traffic to facilitate locomotion with bare hands and standard foodwear. Gloves and special footwear will be available for enhanced locomotion.

People-movers or active locomotion aids will be incorporated into the later years station as needed to meet the emergency egress to safe-haven requirement. The early years connecting passage may utilize a "tow-line" locomotion aid primarily for facilitating the transfer of equipment and logistics supplies.

b. Restraints. The Space Station shall provide the following restraint systems:

- Sleep restraints with adjustable features
- Personal desk "chair"
- Exercise station restraints for upper and lower body exercise
- Dining/meeting table "chairs" - room for ten in one habitat
- "Chalkboard"/briefing station
- Recreation area
- Work stations - restraints for people and material
- Medical examination station
- Restraints for surgical and orthopedic procedures

The restraint systems, as well as other Space Station subsystems, shall be sized to accommodate 5th to 95th percentile males and females.

3.2.6.1.4 Food. The Space Station shall provide food (4.6 lb/man/day) and a food preparation and dining area. The initial Space Station will carry up and resupply all its food needs, and later in the decade up to 50 percent of the crew's diet will be grown on the station.

a. Nutrition/Energy. The Space Station diet will provide about 2,700 calories/man/day. The diet will be composed of approximately 15 percent protein, 30-60 percent carbohydrates, and 30 percent fats. The nutritional content is given in Table 3-23.

b. Palatability. The station diet will provide a mix of thermally stable, frozen, fresh, and freeze-dried foods to optimize variety, texture and taste. Food supplies will include a condiment inventory and provide preflight flexibility of 90-day menu selection and inflight flexibility of weekly menu selection.

Table 3-23. Recommended Daily Dietary Allowances

For a normal healthy man aged 23-50 years (with an average weight of 70 kg and average height of 178 cm) by Food and Nutrition Board, National Academy of Sciences

Energy	2,700 Kcal
Protein	56 g
Vitamin A	100 μg RE[a]
Vitamin D	5 μg[b]
Vitamin E	10 mg α-TE[c]
Ascorbic Acid (Vitamin C)	60 mg
Folacin	400 g
Niacin	18 mg
Riboflavin (Vitamin B_2)	1.6 mg
Thiamin (Vitamin B_1)	1.4 mg
Vitamin B_6	1.1 mg
Vitamin B_{12}	3 μg
Calcium	800 mg
Phosphorus	800 mg
Iodine	150 μg
Iron	10 mg
Magnesium	350 mg
Zinc	15 mg

[a]Retinol equivalents. 1 retinol equivalent = 1 μg or 6 μg beta-carotene
[b]As cholecalciferol. 10 μg cholecalciferol = 400 IU vitamin D.
[c]-Tocopherol equivalents. 1 mg d- -tocopherol = 1 mg α-TE.

c. Storage/Maintenance. The Space Station shall provide storage for 3.6 lb/man/day of shelf stable food and 1.0 lb/man/day of frozen food in the early years. The initial supply will be for five crewmembers for 120 days, including the 150 man-day contingency supply stored in the safe-haven. Early years frozen storage will accommodate up to 70 ft^3 of frozen food at -10F, and approximately 20 ft^3 of refrigerated storage at 40F. Later years refrigerated storage requirement will increase as larger amounts of fresh food are grown on the Station. This additional capability should be incorporated into the dedicated CELSS module. The galley of the first habitat should provide for approximately seven days storage of food for two habitats' crew (ten men).

d. Operations.

1. Retrieval/Harvesting. The galley's food stores should be resupplied weekly from the logistics module. In later years, the crop in the CELSS module will be harvested when ripe, requiring additional crew time on-orbit.

2. Preparation. The galley will provide for the preparation of fresh fruits and vegetables, cutting ingredients and mixing salads, baking bread, and cooking other foods. A fast-cooking oven, such as a microwave oven, shall be provided. Preparation time should not exceed 30 minutes, and two-thirds of the meals should be prepared in 15 minutes or less.

3. Serving. In the early years of Space Station the majority of meals, about two-thirds, will be served on disposable dishes and eaten with disposal utensils. However, one set of permanent dishes and utensils for five will be provided. In the later years, as about 90 percent of the water loop is closed, one-third or fewer meals will be served on disposables, and two sets of dishes and utensils for ten will be provided.

   In the early years about one-third of the meals will be packaged in individual servings. In later years, all meals will be served family style, and only snack food will be individually packed. The dining table in the first habitat will be sized to accommodate ten people.

4. Consumption. Menus will be selected to minimize the need for special equipment and techniques. Meals will be consumed nominally three times per day, and snack food will also be provided.

5. Clean-Up. The galley area will incude a trash compactor, wet-wipes and disinfectant, and a dishwasher with capacity for dishes for ten. Clean-up should not exceed 15 minutes for two-thirds of the meals.

   In later years, a solid waste processor/recycling system will be provided.

3.2.6.1.5 Water. In the early years the Space Station shall provide potable water for the crew in the following quantities:

- 8 lb/man/day for drinking and food preparation
- 12 lb/man/day for personal hygiene
- 50 lb/day for dishwashing
- 11 lb/day for EVA cooling
- 150 man-days of water in emergency amounts

(7 lb drinking, 3 lb hygiene per man per day)

These numbers assume that the dishwasher will be cycled once/day and that there will be enough water for two to three showers per man per week and four handwashers per man per day.

In the later years the Space Station will provide:

- 8 lb/man/day for drinking and food preparation
- 24 lb/man/day for personal hygiene
- 100 lb/day for dishwashing
- 22 lb/day for EVA cooling
- 28 lb/man/day for clotheswashing
- 150 man-days of water in emergency amounts (10 lb/man/day, no dishwash or clotheswash)

These numbers assume that approximately 90 percent of the station's water is reclaimed.

The water is intended to provide two cycles per day of dishwash, four to six showers per man per week, four handwashes per man per day, and one clotheswash per man per week.

The quality of the water provided will be in accordance with NASA MSC Spec SD-W-0020 (May 1970). There will be drinking water dispensers in the galley, private quarters, and work areas. Hot (140F) and cold (45F) water will be provided at the galley.

It will be a design goal to achieve 90 percent closure of the water loop within five years.

3.2.6.1.6 Waste management. The Space Station shall provide the following waste management capabilities.

a. Urine and Fecal Collection and Processing. Subsystems compatible with male and female crewmembers will be located in each habitat, in the safe-haven, and, in the early years, a 450 man-day system will be located in the logistics module. These systems will provide processing

for suppression of bacterial growth and odor control, and will provide for interfacing with automatic urine and fecal measurement, sampling, and preservation subsystems. In later years, both solid and liquid wastes will be recycled to derive water and usable organic solids.

b. Emesis/Expectoration Collection and Processing. In addition to the waste collecting capabilities of the urine and fecal collectors, the Space Station shall provide for oral hygiene needs in private quarters and shall provide emesis stations in each separate manned element.

c. Waste Water Collection. The Space Station shall collect waste water, in early years, in tanks with periodic overboard dump. In later years waste water will be reclaimed as discussed in Subsection 3.2.6.4.

d. Other Solid Waste. In early years, the Space Station will provide for compaction and return to Earth of waste food, trash, and other solid waste. In later years, such waste will undergo an oxidation process and become part of the partially closed EC/LS subsystem.

3.2.6.1.7 Personal hygiene. The Space Station shall provide for body cleansing, both hand washing and whole body showering. There shall be a handwash station in each habitat and in the safe-haven. There shall be a shower facility in each habitat, and the hygiene water budget shall provide for two to three showers/week in early years and four to six showers/week in later years. Wet body wipes shall be provided for cleansing during non-shower days.

In addition, the Space Station shall provide equipment for grooming support, including waterless shaving, haircuts, and fingernail/toenail cutting. Deodorant, mouthwash, and similar odor-masking chemicals shall be provided in the station's general supplies, in addition to personal stocks of such items.

3.2.6.1.8 Clothing. The Space Station shall employ standard-issue type clothing for interior on-duty hours. This clothing shall have multiple closeable pockets and other zero-g conveniences. The standard-issue clothing shall be available in different colors and provide for adjustments to changes in body dimensions.

For off-duty, sleeping, and undergarments, each crewmember shall utilize his/her own garments from Earth. In the early years, each week's dirty laundry will be transferred to the logistics module for return to Earth. Each crew member shall bring 45 changes of undergarments and 23 changes of overgarments. In the later years, each crewmember shall bring seven changes of undergarments and three changes of on- and off-duty clothing. Clotheswashing shall be done once/week.

Personal protective clothing shall be provided for polar, HEO, and GEO radiation hazards, chemical handling, fires, and other needs arising from hazardous operations.

3.2.6.1.9 Communications. The Space Station will provide for communication within the station, for EVA, and station-to-ground as follows:

- There shall be voice intercom stations connecting:
  - -- private quarters
  - -- command and control center
  - -- wardroom/dining area
  - -- EVA Airlocks (plus one-way video)
  - -- each work station (mission modules)
  - -- the interconnecting passageway
- Voice communication from EVA crewman to EVA crewman
- Voice communication from EVA crewman to command and control center (plus one-way video)
- Station-to-ground communication including:
  - -- command and control center to mission control center (voice, video, data)
  - -- emergency back-up voice capability
  - -- work stations to mission control center (voice, video, data)
  - -- private (encrypted) communication (voice/video/data) for personal, medical, commercial, and national security purposes

3.2.6.1.10 Operational medicine. The Space Station shall provide the medical equipment and facilities and appropriately trained personnel to maintain crew health on-orbit, provide countermeasures against undesirable space adaptation effects, and treat illnesses or injuries occurring inflight.

a. Health Maintenance Station. Beginning with the first manned mission, the Space Station shall provide a basic inflight operational medical capability consisting of the Shuttle Orbiter Medical System (SOMS-A) upgraded to include a microbiology kit and instrumentation and reagents kits for automated blood and urine chemistries. The health maintenance station shall also include a friction treadmill and upper body exercise device, an electrocardiograph, and a medical data system interface. In the first few years upgrades should include expanded diagnostic capability in the microbiology and biochemistry kits, a medical imaging system, improved medical life support systems (resuscitator, defibrillator, IV fluids device, rehydratable IV fluids), countermeasures devices, and computer-assisted diagnostic software.

b. Dedicated Health Maintenance Facility (HMF). The HMF consists of rack, floor, and wall mounted equipment and supplies in a separate area, about 15 m^3 of the second habitat. It includes provision for bioisolation, quarantine and support of one crewman, creation of a sterile field for

surgery, and two-way video communication (station/earth). The HMF contains and exceeds all capabilities of the health maintenance station, including a more diversified exercise capability with about ten different cardiovascular stress and coordination exercise devices.

It is anticipated that this upgraded capability will be warranted by the fourth or fifth year when the crew size reaches ten and the second habitat is launched.

c. Hyperbaric Airlock. The hyperbaric airlock will be required at the beginning of manned station operations. It will require a pressurized volume of 150 ft^3 (4.2 m^3), large enough for two suited crewmen, and have the capability to be pressurized to 3 atmospheres (44.1 psia) for 24 hours. It will include voice communication, one-way video, electrical and data interface for simple physiological monitoring, and a small glove-box sized airlock as pass-through for instruments and supplies.

d. Radiation Shielding. Radiation protection requirements are discussed in Subsection 3.2.6.1.1.c.

3.2.6.1.11 Safety. The safety requirements of the Space Station relate to its internal environment, architecture, food, water, waste management, communications, and medical capabilities. The assumption of an early years' rescue capability of 21 days drives all requirements concerning emergency logistics. It is further assumed that by the mid-1990s the rescue capability will be about 14 days. As a result of these assumptions, a safe-haven will be provided with 150 man-day capability in life supporting logistics. Degraded atmospheric, water, and food standards will be tolerated. In addition, when the station has two habitat modules, there shall be the capability to support two habitats' crew in one habitat with somewhat degraded standards. Degraded levels are listed in Table 3-24.

Other safety requirements are as follows:

- Provide redundancy in ECLSS
- Provide one complete module repressurization for one habitat and safe-haven
- Provide for isolation and repair of leaks
- Provide portable O_2 supplies: mission modules, 2 men/4 hrs each; habitat and safe-haven, total crew/4 hrs each
- EVA restricted to "safe" 18 hrs of low-inclination LEO; additional EVA personal shielding required in polar LEO and HEO
- Provide smoke detectors, and non-toxic fire extinguishers in each module
- Each pressurized module is able to be sealed-off from rest of station within 30 seconds

Table 3-24. Contingency Requirements for ECLSS

	90-Day Degraded	21-Day Emergency
Total Pressure	10-14.7 psia	10-14.7 psia
O_2 Partial Pressure	2.4-3.8 psia	2.3-3.9 psia
CO_2 Partial Pressure	7.6 mm Hg (max)	12 mm Hg (max)
Temperature	60-85F	60-90F
Dew Point*	35-70F	35-70F
Airflow	15-30 ft/min	15-30 ft/min
Particulate	300 micron max	300 micron max
Trace Contaminants	8 hr std. (ACGIH)	8 hr std. (ACGIH)
Water (Drink)	7 lb/man/day	7 lb/man/day
Water (Hygiene)	6 lb/man/day	3 lb/man/day
Food	4.6 lb/man/day	3 lb/man/day

*In no case shall relative humidities exceed the range of 25-75%.

- Each pressurized module (except logistics) has two means of access/egress in different locations; between habitat and safe-haven provide two means of access/egress not requiring EVA
- Egress from any manned part of station to safe-haven within 90 seconds.

3.2.6.2 Issues. Convair has identified eleven major crew and life support issues driving the architecture of the Space Station. Briefly stated, they are:

- 14.7 psia atmosphere vs. lower pressures
- Open loop vs. closed loop ECLSS (strategy, time-phasing, etc.)
- Distributed vs. central ECLSS
- Separate experiment modules vs. common mixed-mode design (habitat plus experiments)
- Command and control, EVA station, and safe-haven functions in habitat module vs. general purpose module
- Habitat, general purpose and mission modules same size vs. different sizes (if different, common building blocks vs. hybrid)
- Habitat, general purpose and mission modules returnable to earth vs. in-orbit upgrade only

- Spacelab hardware vs. hybrid vs. external tank
- Zero-g vs. 0.1-g by tether vs. 0.5-1.0-g by rotation
- Crew volume/private quarters volume
- Emergency rescue capability/emergency ECLSS

In addition, another ten issues which are anticipated to have less impact on architecture and cost were identified. These were:

- Vertical continuity within a module.
- Vertical continuity (with respect to cylinders axis) throughout the station.
- Degraded EC/LSS requirements for entire station crew in safe-haven.
- Access and egress (number, location, EVA vs. shirtsleeve).
- Active vs. passive locomotion aid in passageway.
- Early years waste management strategy.
- Passageway (one piece vs. segments connected in orbit as needed).
- Bioisolation of animal module (total volume vs. animal holding facilities only).
- Percentage of diet obtained from fresh food grown on station.
- Palatability of food.

This listing of issues is by no means exhaustive, but these were the items considered by Convair prior to recommending an architectural approach.

3.2.6.3 Options and Trades. For each major issue two or more options were identified and trade-off studies performed. Evaluation criteria included:

- Safety
- Cost
- Station resource managements
  - -- Weight
  - -- Volume
  - -- Power/Energy
  - -- Crew Time
- Complexity
- Reliability

- Flexibility
  (permits technological growth and system evolution)
- Human performance
- Technical risk
- Functional capability
- DOD requirements
- Payload (Science, Application, Commercial) requirements
- Political acceptability

3.2.6.3.1 Atmospheric pressure and composition. The atmospheric pressure selected for the Space Station and associated partial pressure of oxygen and diluent gas will affect many design features of the Station, including:

- ECLSS sizing -- weight and volume
- Logistics/resupply -- weight and volume
- Power consumed in regenerative ECLSS
- EVA suit pressure/O_2 prebreathe requirement
- Materials flammability and offgassing/materials selection program and augmented safety features
- Cooling of temperature sensitive subsystems and cooling the crew
- Seals -- reliability, longevity
- Operational compatibility with Shuttle atmosphere
- Need for unique accommodations for payloads

The trade-off on atmospheric pressure is at present most critically related to the technical risk of the availability and performance of a higher pressure EVA suit which would not require operational encumbrances, such as a 3-hour prebreathe period prior to EVA, and which would possess at least as much mobility and dexterity as the existing 4.3 psia suit. The suit issue is sufficiently important that if an 8 psia suit were not available, a 14.7 psia atmosphere would lose.

Only one alternate option was chosen to trade-off against 14.7 psia, namely 10 psia (34 percent O_2). The oxygen content at 10 psia is dictated by physiological requirements. Ten psia was selected on the grounds of being the highest pressure at which a spacecraft could operate without requiring EVA prebreathing using the current 4.3 psia suit.

The major benefit of a 10 psia atmosphere, assuming availability of a high pressure spacesuit, is the savings on supply and resupply of oxygen and nitrogen. This benefit (a delta of about 1000 lb of launch weight and 500 lb of resupply) trades off against many other disadvantages such as the increased flammability environment of a 3.4 vs. 3.1 psia oxygen atmosphere,

the increased difficulty of cooling electronics and electrochemical systems, and removing crew metabolic heat with the less dense atmosphere, the more stringent materials selection needed, and concern about cross-coupled effects of atmosphere and gravity for payloads such as biomedical research. These reasons for recommending a 14.7 psia atmosphere are summarized in subsection 3.2.6.4.1.

3.2.6.3.2 ECLSS strategy: open vs. closed. Previous studies (ref. 29, 32, 15) have indicated the benefits to be derived from closure and partial closure of an environmental control/life support system. In approaching the options available for a LEO 28.5-degree Space Station ECLSS which requires an initial minimum life support capability of 450 man-days plus 150 man-days contingency between resupply, the issue is not open vs. closed, but rather how soon is it technically and programmatically feasible to go operational with the highest payoff partial closures. (It is assumed that scavenging propellant tanks for oxygen and hydrogen will not be an operational capability until very late in the decade, if at all before 2000; if tank scavenging capability and on-orbit cryogenic storage were available, the open loop option would be a viable alternative.)

The options for system closure thus become: which loops to close first, how much or which sources/uses of each to reclaim, which processes to use, the sizing of each subsystem, and the time-phasing of the operational implementation. The discussion in the Payload Element Synthesis (GDCD 0340, H_2O/CO_2/N_2 Regenerative Systems and GDCD 0341, CELSS Experimental Systems) lays the groundwork for the time-phasing and hardware sizing. A combination of highest payoff (in terms of equivalent weight saved, taking into account initial system weight and power penalties), and technology readiness determine which loops to close first and the selection of processes.

Among the various processes now at a level of developmental maturity appropriate to consideration for a 1990s Space Station are the following:

Water Reclamation

a. Vapor Compression Distillation (VCD)

- Recovers 96 percent of the water from waste water feed
- Prototype hardware has been tested
- Waste water requires pretreatment chemicals and post-treatment in charcoal, ion-exchange beds, and addition of biocide
- Requires about 45-55 watt-hr./lb of water recovered

b. Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)

- Recovers 95 percent of the water from waste feed
- Prototype hardware has been tested (less extensively than VCD)

- Requires pretreatment and post-treatment
- Energy requirement not well established

c. Vapor Phase Catalytic Ammonia Removal

- Requires no pre- or post-water treatment
- Consider for later years experimental system

d. Membrane Processes

- Consider Reverse Osmosis and Electrodialysis for future advanced development effort.

CO_2 Removal

a. CO_2 Adsorbers

- Skylab molecular seive with silica gel sorbent bed
- Solid-amine/thermal-vacuum desorbed
  SA/TVD system has lower weight and volume than Skylab system, reduced cabin heat load, and lower power requirement
- Solid-amine/steam desorbed
  SA/SD system enables interfacing with operational CO_2 reduction subsystem

b. Electrochemical Depolarized Concentrator

- Electrochemical method that continuously removes CO_2 from a flowing air stream and concentrates the CO_2 to a level useful for O_2 recovery
- Operates at higher humidity levels than CO_2 sorbers, operates continuously, and potentially at higher efficiencies
- Lower weight system than CO_2 sorbers

CO_2 Reduction

a. Sabatier Process

- Requires source of hydrogen -- ideal for ECLSS using a hydrazine-based nitrogen generation subsystem
- Prototype units of 98-99 percent efficiency have been demonstrated
- Requires overboard venting of methane exhaust

b. Bosch Process

- Single pass efficiency only 10 percent; requires multiple passes
- Requires disposal of waste carbon
- Requires half as much hydrogen per unit CO_2 removal as Sabatier
- Offers substantial weight savings over Sabatier (when there is no nitrogen subsystem) for missions over 500-man days

Oxygen Generation

a. Solid Polymer Electrolyte Water Electrolysis Subsystem

- Low voltage, no free electrolytes in subsystem
- Three-man system has been demonstrated

b. Static Feed Water Electrolysis Subsystem

- Less complex than SPE/WES, higher reliability
- Low cell voltages, low power penalty
- One-man system has been developed

Nitrogen Generation

- Catalytic dissociation of Hydrazine
- Used for both ECLSS and spacecraft resource (attitude control, etc.)

The recommended approach is summarized in subsection 3.2.6.4.2.

3.2.6.3.3 ECLSS strategy: distributed vs. centralized. A number of options are possible for location of atmosphere supply/revitalization hardware, water supply/reclamation hardware, and waste management hardware. Possibilities considered included everything in a General Purpose Module (open or closed loop), everything (except distribution plumbing) in a Logistics Module (open loop only), everything in Habitat Module (open or closed), Atmosphere subsystems in all manned modules (closed) with waste subsystem in Habitat, General Purpose, and Logistics Modules (open or closed), and Atmosphere subsystems in Habitat and General Purpose Module (closed) only with water subsystems in Habitat and General Purpose Modules (open or closed) only. Numerous other combinations are also possible, but not considered herein.

The reasoning behind the approach selected in subsection 3.2.6.4.3 weighted safety and feasibility as the most important factor, requiring redundant ECLSS systems from IOC and the ability to incrementally upgrade the ECLSS. At the same time, technical risk/technology readiness drives our selected approach towards initially flying an open-loop atmosphere subsystem with experimental (one or two man) systems for zero-g evaluation. Safety considerations further dictate an open loop emergency ECLSS in the Safe-Haven, and operational compatibility suggests that a large portion, if not all of the 90-day supply of atmosphere and water in an open loop system be located in the Logistics

Module. Operational compatibility and crew time considerations also argue for locating the early years' open loop waste management subsystem (fecal collection and solid-trash depository) in the Logistic Module, although the waste collection capability of the LM should not be the only waste collection capability of the Space Station.

These considerations led Convair to recommend the approach summarized in Subsection 3.2.6.4.3.

3.2.6.3.4 Separate experiment modules vs. mixed-mode design. This issue and the next four issues are interrelated. The choices in each case will influence the results of the other trade-offs and the overall recommended approach. The basic issue is modularity of functions, i.e., at which level in the functional hierarchy do we modularize? The answer to this question affects flexibility, cost-phasing and other programmatic considerations, payload compatibility, operational compatibility, complexity, safety, and to a lesser extent, virtually all the other evaluation criteria.

Convair's analysis of the functions which ought to be in separate modules led us to distinguish between Station operations, payload operations and human living accommodations for long-duration space flight. Station operations include command and control, spacecraft data management, communications to ground and EVA accommodations. Payload operations include those functions unique to a given science, applications, technology, DOD or commercial user, and may include support from Station operations functions. Human living accommodations for long-duration spaceflight include those architectural attributes which transcend the basic life support functions and make the Space Station a livable place for a given size crew for three months or more.

It is the last definition which leads us to separate the habitability function from the Station operations function and from the payload or mission function. The Station operations function is recommended to be accommodated in a separate "General Purpose Module" shown in Figure 3-31 which by itself is a man-tended facility, or a short-duration (14-21 days) Space Station. The payload operations function is recommended to be accommodated in separate "Mission Modules", whose number is depended on user requirements, user funding, and module sizing approach. Module sizing is the subject of Paragraph 3.2.6.3.6.

3.2.6.3.5 Location of safe-haven function. The "safe-haven" is a part of the Space Station which possesses a contingency life support capability and all critical Station functions to support the entire crew in an emergency situation for a given period of time. The Convair safe-haven concept requires 150 man-days of life support (air, water, and food at degraded levels and waste management) based on 30 days for 5 men, 21 days for 7 men, or 15 days for 10 men.

Because the critical Station functions, e.g., command and control, are located in the General Purpose Module, the Safe-Haven must also be located in the GPM.

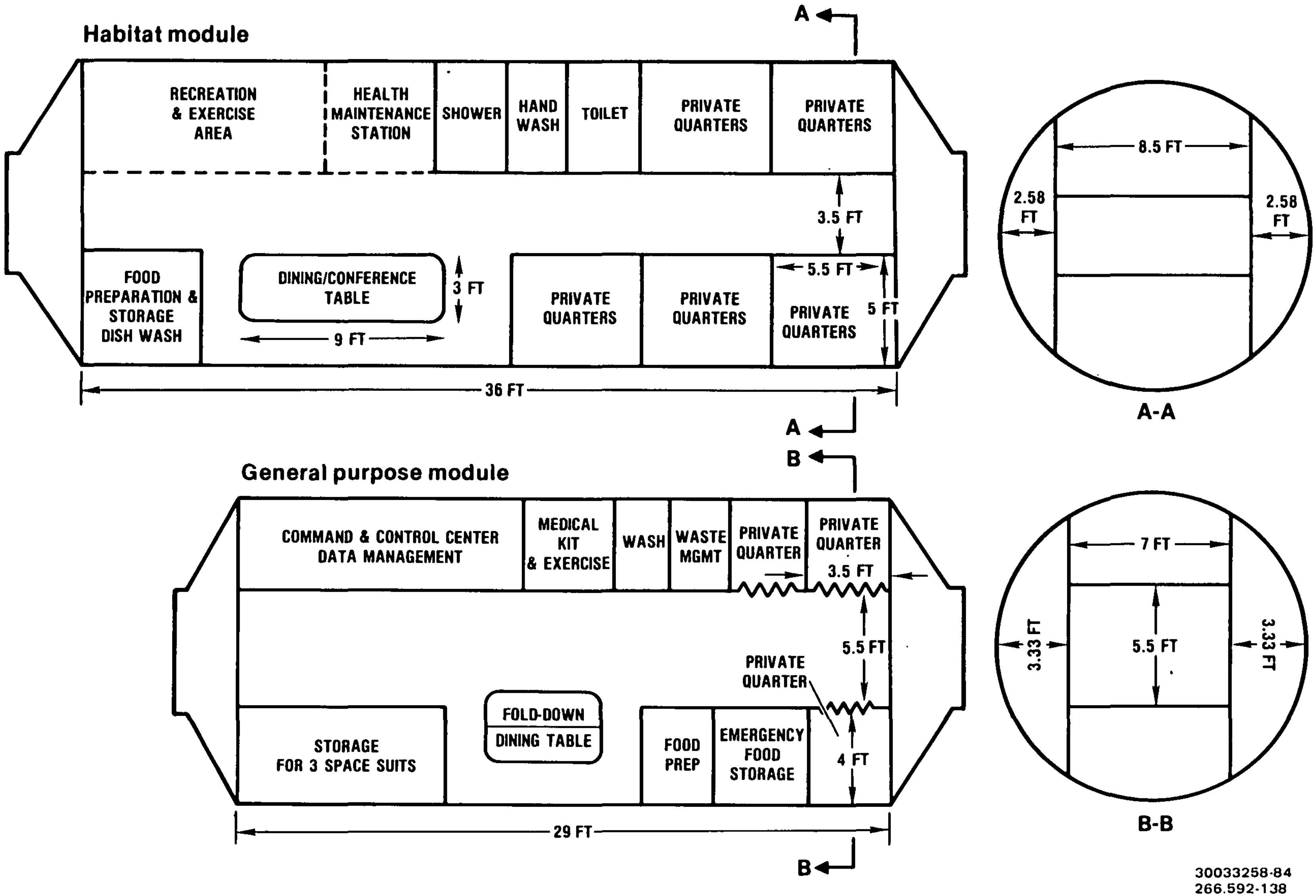


Figure 3-31. Floor Plan Concept for Habitat & General Purpose Module

3.2.6.3.6 Sizing of modules. The volume required by the Station operations, Payload operations, and long-term living accommodations functions are determined by operational and user requirements and apaplication of spacecraft and interior design criteria developed from past spaceflight and analogous Earth-based underwater and antarctic missions. The module size required to accommodate these volumes may be many different sized hybrids. . Several different standard sizes (e.g., small, medium, large) or "one-size fits all". The Convair analysis weighted initial cost most heavily in recommended maximizing the number of same-sized modules, but allowing for common-sized building blocks to enable construction of common diameter cylinders of volume V, 2V, 3V, and 4V.

3.2.6.3.7 In-Orbit servicing vs. return to earth. Convair has made a basic assumption that whenever maintenance, repair, or equipment changeout is feasible in-orbit that would always be the preferred approach. This holds true for entire modules; however, mission modules may be sized so that, without major redistribution of equipment for Shuttle landing C.G., they may be returned to Earth in entirety for major equipment upgrading or reconfiguration. Therefore, it is recommended that mission modules be sized consistent with the recommendation of Paragraph 3.2.6.3.6, to be returnable to Earth.

3.2.6.3.8 Spacelab hardware vs. external tank vs. hybrid. Discussion of the previous three sections was clearly developed with this trade-off in mind. Assumptions and conclusions above argue strongly against use of the ET.

The ET is not recommended for use in the pressurized volume of Space Station in the first decade because of weight, volume and power considerations -- the ET LO_2 tank has 3 times the volume needed for the Habitat and 1.8 times the volume for Habitat plus General Purpose Module (LH_2 tank has 8 times Habitat requirement); to avoid logistics penalty, only a fraction of the ET volume would be used for any manned function. In addition, there are flexibility and technical risk considerations. If all manned functions were combined into the ET (early years requirement met in LO_2 tank) this would be contrary to the modular build-up concept and be undesirable for cost, technical, and programmatic reasons. Finally, there are crew-time considerations. There would be a high penalty on crew time needed to set up spent ET in orbit.

It is anticipated that there would be a substantial cost advantage to most payload developers to use Spacelab hardware in the Mission Modules. Many user groups will have developed and flown Spacelab compatible instrumentation, representing both a cost and reliability advantage.

The Habitat and General Purpose Module (Figure 3-31) will involve major reconfiguration from the existing Spacelab design. Although Spacelab shell segments are potentially useful, new hybrid building blocks should be considered.

3.2.6.4 Selected Approach. For each of the eight major crew and life support issues presented in subsection 3.2.6.2 plus the other thirteen issues mentioned in that section, Convair's recommended approach is summarized below:

3.2.6.4.1 Atmospheric pressure and composition

Recommendation	Reasons
Provide a 14.7 psia, 21-22 percent oxygen atmosphere starting at IOC. (This assumes operational availability of 8 psia suit with mobility and dexterity comparable to current EVA suit.)	Safety -- lower flammability, lower off-gassing, less stringent materials selection. Reliability -- better cooling of electronics and other heat sources Operational compatibility with Shuttle Payload Accommodation -- biomedical experiments

3.2.6.4.2 ECLSS strategy: open vs. closed

Recommendations	Reasons
1. Launch Open Loop System (5-MAN) using Shuttle technology and, as experiments, launch 2-man water recovery system for cabin humidity condensate recovery via multi-filtration and wash water and urine recovery via thermoelectric integrated membrane evaporation system.	Safety -- Proven technology, low technical risk.
2. Partial (33-40 percent) water loop closure operational within first year; 90 percent closure within three years (entire crew).	Weight and Cost -- Water is highest logistic penalty/fastest dollar payback to reclaim
3. Launch 2-man CO_2 removal system (as experiment) within first two years using solid amine-steam desorbed process; operational CO_2 removal -- 100 percent excluding EVA -- within first four years (entire crew).	Weight and Cost -- CO_2 removal is second highest logistics penalty
4. Launch two-man O_2 generation system (as experiment) within first three years, using solid polymer electrolysis process; operational O_2 generation within first five years (entire crew).	Weight and Cost

Recommendations	Reasons
5. N_2 generation (experiment), two-man system using catalytic dissociation of hydrazine, within four years; operational system within first six years	Weight and Cost
6. CO_2 reduction (experiment), two-man system using Sabatier process, within three to four years; operational system within five to six years.	Weight and Cost
7. Grow food (as experiment) e.g., lettuce, tomatoes, wheat, peanuts, soybeans, during first five years; operational food production for 33 percent of crew needs within six to seven years. (Assumes crew of 12.)	Weight and Cost Human Performance
8. Launch 2-man solid waste recycling system (experiment) using wet oxidation process within first 4 years; operational system within 6-7 years.	Weight and Cost

The ECLSS strategy is summarized in Figure 3-32.

3.2.6.4.3 ECLSS strategy: distributed vs. centralized

Recommendation	Reasons
Early years' open loop system is central plant in logistics module with back-up water, O_2, CO_2 removal, N_2, Food and Waste Collection in Safe-Haven; during second-sixth year ECLSS becomes distributed, partially closed-loop system with water, O_2 generation and CO_2 removal in Safe-Haven, Habitat and mission modules and N_2 and waste management in 2-3 locations.	Safety -- redundant systems in parallel Flexibility -- ease of upgrading technology

3.2.6.4.4 Separate experiment modules vs. mixed-mode design.

Recommendations	Reasons
Separate Experiment modules	Flexibility
Separate Habitat modules	Human Performance
Separate Station Ops/Command Center/ EVA Center	Cost-Phasing/Programmatics/Payload compatibility

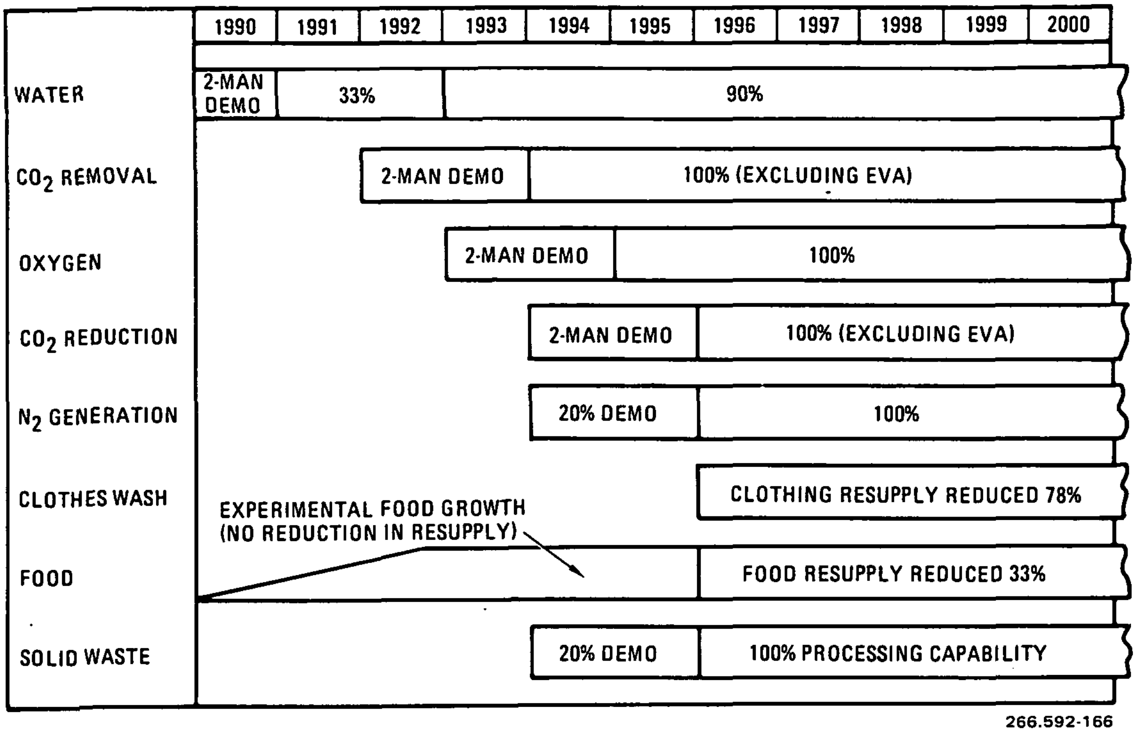


Figure 3-32. EC/LSS Time Phasing

3.2.6.4.5 <u>Safe haven/station operations: habitat vs. separate module.</u>

Recommendations	Reasons
Safe-Haven (21-day emergency life support) plus Command and Control plus EVA	Flexibility -- ease of establishing initial manned presence
Station in separate "General Purpose Module"	Complexity -- simplifies Habitat module
	Human Performance -- keeps "work" out of habitat
	Safety/Cost -- lowers the cost of Safe-Haven capability; 25 percent less pressurized volume

3.2.6.4.6 <u>Habitat, station ops, mission (R, D, & P) modules: same size vs. different sizes.</u>

Recommendation	Reasons
Size dictated by payload and operational requirements - use minimum size made from common building blocks, e.g., pressurized volumes = V, 2V, 3V, etc.	Flexibility Cost

3.2.6.4.7 Modules returnable to earth via the shuttle vs. in-orbit repair maintenance, upgrade only.

Recommendation	Reasons
Mission modules generally sized to be returnable, but maximum use of in-orbit maintenance, repair, and change-out to upgrade.	Flexibility - evolutionary growth Technical risk

3.2.6.4.8 Spacelab hardware vs. external tank vs. hybrid.

Recommendations	Reasons
Spacelab hardware for R, D, & P mission modules - maximum use	Cost -- Payload developers have hardware to fit Spacelab
Spacelab shell segments or hybrid segments plus new interior and systems for Habitat and General Purpose Module	Reliability -- Spacelab hardware will have flown in space
ET not recommended for use in pressurized volume of Station in first decade.	Selection of Spacelab for Habitat and GPM will depend on design configuration - different floor/ceiling requirements and few rack requirements may indicate cost benefit with complete new build
	Weight, Volume and Power -- The ET LO_2 tank has 3 times the volume needed for Habitat and 1.8 times the volume needed for Habitat plus General Purpose Nodule; (LH_2 tank has 8 times Habitat requirement). To avoid logistics penalty, only a fraction of the ET volume would be used for any manned function
	Flexibility and Technical Risk -- If all manned functions were combined into the ET (entire early years requirement met in LO_2 tank) this would be contrary to a modular build-up concept and be undesirable for cost, technical, and programmatic reasons.
	Crewtime -- High penalty on crewtime needed to set up spent ET in orbit

3.2.6.4.9 Zero-G vs. 0.1-G by tether vs. 0.5-1G by rotation.

Recommendation	Reasons
Zero-G	Technical Risk -- Tether technology not proven Cost -- Rotation would add substantially to cost of Station Complexity -- Would alter design throughout Station Human Performance -- Rotation at feasible radii results in undesirable coriolis effects.

3.2.6.4.10 Crew volume and private quarters volume.

Recommendation	Reasons
$120m^3$ Habitable Volume in Habitat Module, with $25m^3$ for Private Quarters for 5 ($5m^3$/man)	Human Performance Functional Capability

3.2.6.4.11 Emergency rescue capability/emergency ECLSS.

Recommendation	Reason
Assume a 21-day Shuttle rescue capability in early years; provide a safe-haven with 150 man-days' supply of life supporting logistics; assume a 14-day rescue capability in later years, and no growth in the safe-haven; eventually a capability will be available.	21-day assumption provided by NASA; assume 14-day Shuttle capability by mid-late 90s, also on-call manned space vehicle capability by late 90s.

3.2.6.4.12 Vertical continuity within a module.

Recommendation	Reasons
Consistent Vertical Orientation	Human Performance -- Early crew adaptation, avoidance of disorientation and possible motion sickness.

3.2.6.4.13 Vertical continuity (with respect to cylinders axis) throughout the station.

Recommendation	Reasons
Same local vertical (vertical aligned with radial dimension, horizontal aligned with axis) in every manned module. (But vertical from module to module; not necessarily aligned.)	Cost -- Spacelab precedent Human Performance -- Early crew adaptation

3.2.6.4.14 Degraded ECLSS requirements for entire station crew in safe-haven.

Recommendation	Reasons
21-day emergency capability in GPM and 90-day degraded capability for 2 Habitats crew in one habitat. See Table 3-24.	Cost Flexibility

3.2.6.4.15 Access and egress; number, location, EVA vs. shirtsleeve.

Recommendation	Reason
2 Access/Egress Routes per pressurized module, different locations, one may require EVA; 2 access/egress routes between habitats, and between habitats and safe-haven (not requiring EVA).	Safety

3.2.6.4.16 Active vs. passive locomotion aid in passage way.

Recommendation	Reasons
Passive Aids (Handholds, Footholds) Adequate to meet 90 sec requirement to safe-haven; towline/people and equipment-mover provided for equipment/logistics transport	Safety Human Performance Functional Capability

3.2.4.6.17 Early years' waste management strategy.

Recommendation	Reasons
Shuttle-size waste management compartment in Safe-Haven, Double-Size (450 man-days) WMC in Habitat and Logistics Module; LM WMC used most of the time to minimize changeout of fecal canister in HM and GPM; when closed-loop solid waste is operational, LM WMC is eliminated (may become hardware for habitat No. 2).	Crew Time Operational Compatibility Flexibility

3.2.6.4.18 Passageway: one-piece vs. segments connected in orbit as needed.

Recommendation	Reasons
One-Piece passageway/docking and berthing	Safety Reliability Complexity Operational Compatibility

3.2.6.4.19 Bioisolation of animal module: total volume vs. animal holding facilities only.

Recommendation	Reasons
Provide particulate, odor, and bacterial filtering of atmospheric effluent from animal facilities, and means to work on and transfer animals without contaminating ambient air	Human Performance Operational Compatibility

3.2.6.4.20 Percentage of diet obtained from fresh food grown on station.

Recommendation	Reasons
No aminal food, i.e., fresh meat, in first decade; higher plants, e.g., lettuce, tomatoes, wheat, peanuts, plus algae, e.g., spirulina, and yeast to make up approximately 33 percent of crew diet in later years.	Human Performance -- Fresh food (good) but 100 percent fruit, vegetable, grain and nut not acceptable to many. Technical Risk -- Must first verify plant growth development and reproduction in Zero-G Programmatic -- Initial cost investment with payback in later years (logistics savings); percentage limited by dollars available up front Operational Compatibility -- Fresh meat doses; large operational impacts

3.2.6.4.21 Palatability of food.

Recommendation	Reason
With a goal of maximizing palatability, i.e., taste, texture, variety, and allowing for personal preference, at least half of the crew's diet should be frozen and thermal-stable (e.g., canned, partially dried) foods; introduce fresh foods, e.g., fruits, salad, bread, within first year	Human Performance

3.2.6.5 Crew Support Subsystem Technology Needs

3.2.6.5.1 Atmosphere revitalization

- CO_2 Removal: Complete development of electrochemical depolarized concentrator and solid amine/steam desorbed systems
- O_2 Generation: Flight demonstration of solid polymer electrolysis system
- CO_2 Reduction: Flight demonstration of Sebatier reactor, development of self-cleaning Bosch reactor, analysis of uses for Bosch carbon
- N_2 Generation: Development of hydrazine cracking module
- Trace Contaminant Control: Development of catalytic oxidizer

3.2.6.5.2 Water reclamation

- Complete development of vapor compression distillation and thermoelectric integrated membrane evaporation system
- Develop hyperfiltration process with low temperature membrane
- Develop multifiltration process
- Develop water quality monitor

3.2.6.5.3 Waste management

- Develop replaceable fecal canister for Shuttle-type system
- Develop supercritical oxidation process
- Develop trash compactor

3.2.6.5.4 Food.

- Selection of diet/optimum plant species/light/growth media
- Study of zero-G influence on plant development
- Development of cultivation methods and equipment

- Selection and development of unconventional food sources (e.g., algae)
- Development of zero-G oven, refrigerator, and freezer
- Development of zero-G Dishwasher

3.2.6.5.5 Systems integration.

- Automatic control systems for air, water, food, and waste
- Integrated systems development for air, water, food and waste systems with energy management and attitude control systems
  - -- Cryogenic transfer of scavenged O_2 and H_2
  - -- Math modeling of partially closed ECLSS integrated with Space Station H_2-O_2 systems.

3.2.6.5.6 Hygiene equipment.

- Develop zero-g shower and handwash
- Develop zero-g clotheswasher and dryer

3.2.6.5.7 EVA support.

Development of:

- High pressure (e.g., 8 psia) suit
- High dexterity glove
- Non-venting EMU PLSS thermal control subsystem
- Regenerative EMU PLSS CO_2 removal subsystem
- Recharge Station for EMU O_2 and suit dryer
- Combustion propulsion for MMU
- Two-stage air pump for EVA airlock

3.2.6.5.8 Operational medicine

- Zero-g norms, zero-g kinetics of pharmaceuticals
- Zero-g surgical and orthopedic procedures
- Tissue sampling and handling
- Hardware - diagnostic imaging, clinical chemistry, automated hematology and urinalysis, microgiology, miscellaneous diagnostic and therapeutic equipment, rehydratable IV fluids
- Modularization and trade-offs for dedicated health maintenance facility
- Computer-aided diagnostic/therapeutic checklist

3.2.7 OPERATIONS MANAGEMENT. The establishment of permanently manned, long term space facilities presents many new and challenging problems in operations management. All manned space programs to date have only had to deal with relative short stay times on orbit of short lived orbiting facilities. The space shuttle, for example, has a stay time of about seven days. Each mission is thus well rehearsed, its procedures validated, and its crew well organized to assure the best utilization of time on orbit and mission success. This is all painstakingly worked out on the ground months in advance of the mission flight.

During the Space Station era greater reliance on the autonomy of the crew to manage the operation of the station is envisioned. This subsection suggests approaches for enhancing that capability.

3.2.7.1 Obstacles to Autonomy. There are a number of major issues to be addressed in determining suitable operations management concepts that will give the Space Station crew a significant measure of autonomy while reducing the need for extensive ground based support. Rather than dwell on some of the basics of management such as organization structure, procedures, policies, etc., it would seem more appropriate to first identify some of the major obstacles to crew autonomy, then postulate potential ways to resolve them. Among these obstacles are:

a. Time and effort devoted to day-to-day management activities, such as planning activities, problem solving, improving and updating skills and techniques, taking inventories, ordering supplies, and controlling work progress.

b. Lack of the broad base of expertise on systems hardware and software usually vested in the operations support contractors and/or lack of adequate on-board fault detection/identification capability to preclude extensive ground backup support.

c. Potential conflicts over the control of missions planning and missions operations between the Space Station user community and the Space Station Operating Authority. These include such things as setting missions priorities, creating interferences or interruptions in user processes, and compromising user security requirements.

3.2.7.2 Ways to Achieve Greater Autonomy. The time problem associated with daily management of station operations can be resolved through a well organized on-board management information system and a highly automated material control system. These systems would be used to continuously track work progress against preplanned schedules, utilization and status of consumables, status and location of parts and materials, and update work schedules on a day-to-day basis. Resupply needs would be projected in advance of the next Shuttle visit to allow cargo manifests to be prepared well ahead of time.

Missions operating procedures and schedules would all be preplanned by the user and the Space Station Operating Authority. However, once a mission was placed on-board the Space Station, the designated mission specialist would assume control of that mission, but would have to abide by the regulations governing the use of the Space Station.

The on-board solution of hardware and software anomalies suggests the need for expert systems, i.e. computer systems that are programmed with the necessary expertise to identify the cause of systems anomalies and prescribe corrective action.

Many would argue that this is not achievable because most unexplainable anomalies occur as a result of unanticipated causes that become apparent only after careful failure analysis. The Space Station, however, does lend itself to the application of established techniques for detecting incipient failures in hardware systems. This is due to its ability to process data from many sensors that could be installed throughout the system for the purpose of detecting failures before they occur. Such an approach, coupled with a prudent use of fault tolerant systems design, could avoid the need for an extensive ground backup team approach.

Obviously conflicts will arise between Space Station users due to unscheduled delays in missions that cause other missions to be interrupted or rescheduled. Priorities will have to be set by the Space Station Operating Authority in order to allow the Space Station operations crew to maintain control of station activities.

3.2.8 AUTOMATION AND CONTROL. An effective and reliable automation of the future Space Station is needed to improve man's efficiency in using its facilities. This subsection treats concepts of automated elements and their supervisory control. The tasks and functions which can be automated are identified and an architectural structure that satisfies these functions by technological assets of the 1980s is recommended. Use of the Remote Manipulation System (RMS) and its miniaturized derivative is suggested for station's external and internal applications. Furthermore, relevant technologies required in the automation and control have been identified. GD Convair's experience in developing a dual failure tolerant control system for the Shuttle/Centaur mission is applicable to the Space Station automation and control.

3.2.8.1 Practical Automated Systems. The conscious combining of human and machine capabilities into an integrated engineering system is a most complex and highly interactive interdisciplinary undertaking. Remote machine operations under human control further stretch our skills and knowledge of human/machine interaction. Such human controlled remote systems are referred to as Remote Manipulation Systems. The RMS are useful to extend and enhance the human's capability to perform specific tasks in the space environment. They are machine systems under the control of a human operator who manages the system from a remote site.

These systems are comprised of the following components:

a. The Operator's Work Station, providing control and display information for the human so that remote tasks can be carried out at the work site through the RMS arm. The operator's work station should have provisions for remote scene feedback via television; provisions for remote system mobility via hand controllers or switches; and provisions for systems status monitoring via indicator lights, meters, computer printouts, and video display terminals (VDTs).

b. The Interface Unit for transmitting and receiving communications between the operator and effector unit, for computational assistance in coding, decoding commands and activities, and for transformation of data between the operator and effector unit.

c. The Remote End Effector or Actuator Unit, providing capabilities for sensing, manipulation and mobility at the remote site. The proposed sensors are television cameras with on-board lighting. Proposed mobility subsystems depend upon application, but generally permit movement in six degrees-of-freedom (DOF) for the unit. The manipulative devices will generally reflect the nature of the task from simple moving of logistics, to servicing and repair activities.

In order for the human operator to fully understand and appreciate the remote site, it is necessary for the remote system to have on-board sensory instrumentation which can relay data to the operator. Forces, torques, pressure, speed, temperature, vision and acoustic information might be desirable for spcific applications. The remote system can be designed to sense information beyond the range of the human and can transform this information for human interpretation. The displays must be compatible with operator limitations and mission requirements.

General and special purpose manipulators can perform a wide range of effective tasks at the remote site, particularly with specialized end effectors such as tool attachments. The manipulators can resemble human arms or they can be made longer, thinner, stronger, and more dexterous than human arms, or designed to almost any specification required by the task.

While considerable electromechanical advantage can be obtained with the remote system, the state-of-the-art in artificial intelligence does not currently approach that of the human. While local programs for very specific tasks can be realized, it is recognized that the primary decision making tasks are allocated to the human. As research improves artificial intelligence, this balance will shift and we will move closer to autonomous remote systems.

As a system which extends and enhances the human's capabilities, Remote Manipulation Systems take on numerous forms and perform many functions, but each shares the characteristics of:

a. Human command/control.

b. Communication control and feedback interfaces.

c. Remote mechanical effectors for mobility and manipulation.

The proposed RMS applications for Space Station service involves short distances between the control station and the effecting or actuating unit. However, these distances do not preclude defining human-attached systems such as exoskeletal work amplifiers or prosthetic devices from being included in the general RMS class. Furthermore, where remote systems are partially managed by programmed computer subroutines and the human operator maintains a supervisory or override capability, these systems could fall under the category of RMS as opposed to autonomous systems such as robots.

3.2.8.2 Space Station Automation

3.2.8.2.1 Mission Applicability. Study of Space Station Needs, Attributes and Architectural Options has revealed a need for application of automated elements to assist in rendezvous, deployment and maintenance of the OTV, TMS and the free flyer satellites at the man-tended Space Stations. Based on these needs the Space Station must provide shelter and services to the above mentioned space vehicles. These services include examination, removal and replacement of the defective assemblies, as well as the capability to refuel the vehicles. The fundamental needs for automation and robotics are driven by the required safety, reliability and operational efficiency of the minimally staffed Space Station.

3.2.8.2.2 Considerations in robotics design. Some considerations for determination of Space Station robotic elements and their feasibilities are:

a. The robotic device must have a stable platform for its manipulators.

b. Components of a robotic device, the body, and manipulating arm should be as thermally insensitive as practical so as to maintain positioning accuracy.

c. The manipulator and gripper should have at least a total of six degrees of freedom for maneuvering flexibility.

3.2.8.3 Automated Tasks. Based on the space vehicular servicing operations analysis of subsection 2.2.1.4, it is clear that with a minimum human staff the Space Station must be automated in order to perform its required tasks. Table 3-25 lists the typical tasks which can be automated by use of three prominent elements:

a. Remote Manipulating System capable of acquiring and moving bulky loads on the periphery of the space service station.

b. Small RMS capable of demounting and replacing astrionic units on OTV, TMS and the FFS. This particular manipulator is to be moving on rails within the service compartment for each of the space vehicles associated with space service.

c. The service cradle element capable of extending itself out of the service shelter and acquiring the space vehicle for its eventual service within the service shelter.

3.2.8.4 Automated Elements

3.2.8.4.1 Remote manipulation system (RMS). The Remote Manipulation System (RMS) is similar to the one used on the Orbiter STS. The RMS base is placed on rails outside of each service station tube where its locomotion is restricted to a propagation from one end of the tube to the other. It shall be moved under the control and supervision of the regional computer program and CCTV (man-in-the-loop) subsystem. Details of RMS parameters and performance are available in NASA's technical publications on the Space Transportation System.

Table 3-25. Supervised Automated Functions

FUNCTION	AUTOMATION ELEMENT USED			SPACE VEHICLE SERVICED		
	RMS	SRMS	SCE	OTV	TMS	FFS
Space Station Construction	X					
Assembly Work	X	X		X		X
Extending Docking Cradle			X	X	X	X
Docking Assistance	X			X	X	X
Vehicle Acceptance	X		X	X	X	X
Inspection		X		X	X	X
Cleaning		X		X	X	X
Adjusting		X		X	X	X
Deploying Diagnostics Umbilical		X		X	X	X
Removing SRU		X		X	X	X
Moving Parts and Logistics	X	X		X	X	X
Replacing SRU		X		X	X	X
Connecting Fuel Line		X		X	X	
Controlling Fuel Valves		X		X	X	
Disconnecting Fuel Lines		X		X	X	
Replacing Energy Panels	X	X				X

SRU = Space Removable Unit
RMS = Remote Manipulation System
SRMS = Small RMS
SCE = Service Cradle Element
OTV = Orbital Trans. Veh
TMS = Teleoperator Maneuvering System
FFS = Free Flyer Satellite

The RMS arms of the relevant service stations are used during rendezvous and docking of: OTV + TMS + FFS, TMS + FFS, OTV or TMS arriving in combinations or separately depending on the mission. The RMS can also assist in mission deployment as well as fetching parts from the logistics support area.

3.2.8.4.2 Small remote manipulators (SRM). The Small Remote Manipulating System is similar to the RMS but scaled down dimensionally and energetically. One or more SRMS could be placed on rails inside of each OTV service shelter. The rails would run parallel to the centroid of the cylindrical service tube. This allows a 360-degree coverage along the length of OTV when it is inside of the shelter. The SRMS, under the command and control of the central data

bus and supervision of a person in the command module is capable of moving to its task position and executing a program relevant to that task. Typical of the tasks may be unbolting, disconnecting, removing, moving, servicing, and replacing the astrionic SRUs on OTV, TMS or the FF satellites. The task programs may be addressed to one of the SRMs or to the concerted effort of two adjacent SRMS. The commands and monitor interfaces between the regional computer data bus and the SRMS robot in motion may be established by use of either infrared or optical beam emitters and detectors. Further study of the command data and the CCTV interface video link technologies are recommended.

Each SRMS uses a highly reliable and space hardened microprocessor with a dual failure tolerant and fail safe redundant control system. The SRMS are also outfitted with a high resolution close circuit TV camera and the illumination of work site subsystem. The CCTV monitors are placed in a command module for the human viewing and interaction. In case of a faulty move by a SRMS arm, it can be stopped immediately by a direct command from the central monitor and command seat.

3.2.8.4.3 Service cradle and docking element. Service Cradle and Docking Element is used at each vehicle service station to acquire, receive and provide a service bed for the space vehicle requiring service or shelter. The element consists of ranging devices, servo loop motion system, and a microprocessor based control unit. Ranging status and the task command data is processed by a local microprocessor and then multiplexed into a format of the regional data bus.

The service cradle performance is controlled by a local microprocessor and the CCTV human observer when extending the cradle to the space vehicle, docking with it, and/or bringing it into the service station. Either local or remote human observer is always in the control loop of cradle operations. Docking and cradling effort may be distributed between the RMS and the SCE subsystems. Such an effort, however, is always coordinated by a regional processing unit and a human observer.

3.2.8.5 Control Architecture. The operational control of the automation elements described in paragraph 3.2.8.4 is achieved by use of functional architecture shown in Figure 3-33. The automation control architecture is based on the autonomous but subordinated general purpose computer unit whose function is to coordinate controls and supervision of the automated elements located in the individual service compartments of the Space Station. This architecture is comparable with the reliability scheme used on the Orbiters STS. The standard regional processor manages programs relating to the automation and robotic elements which are equipped with high performance microprocessors capable to execute automated tasks within their area of competence.

Command and data signals from the serial regional data bus are demultiplexed by the Station's Remote Multiplexing Unit and then distributed to the individual automation service links. Status data destined to the regional data bus is serialized by the automated element local microprocessor and then multiplexed into the regional data bus format by the Remote Multiplexing Unit. The command and status signals between the Multiplexing Unit and the

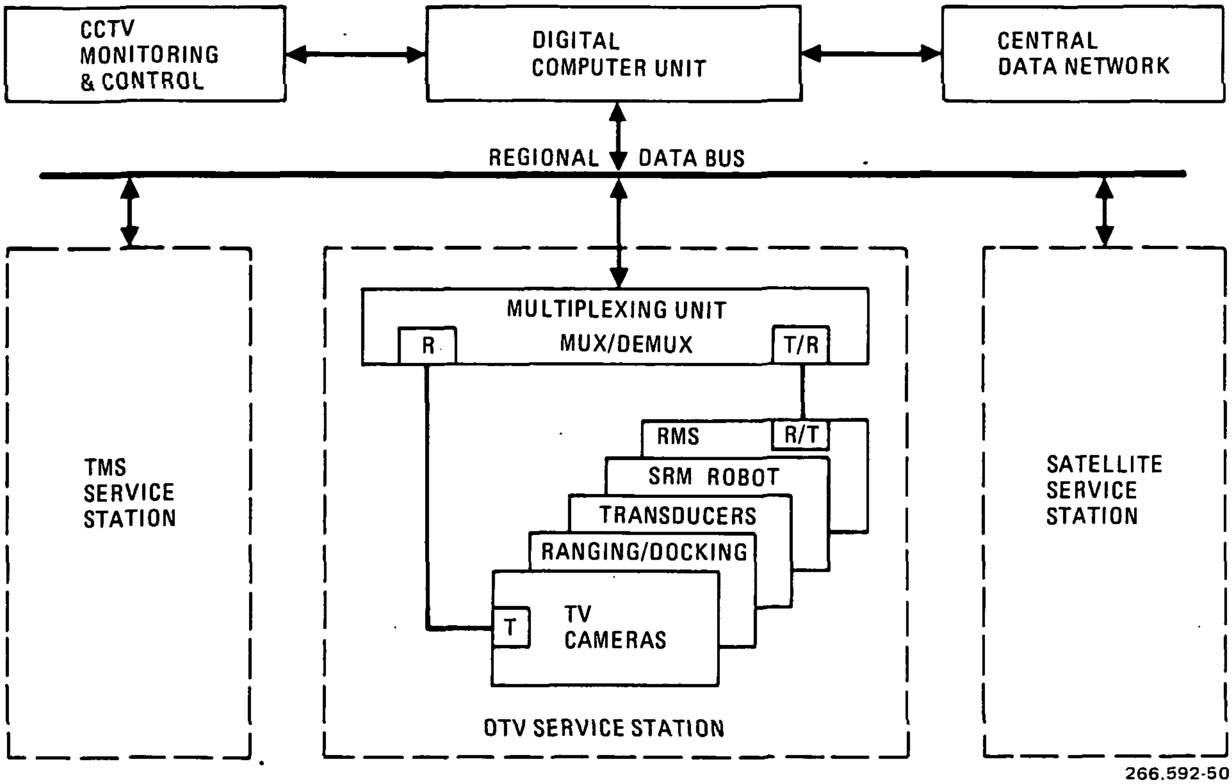


Figure 3-33. Automation & Control Architecture

Unit and the moving automated devices such as moving RMS/SRMS robots will be propagated by use of yet to be determined emission subsystem. Few candidates such as infra red (IR) emission, low power He-Ne laser, or the ordinary collimated Light Emission Diode (LED) should be explored. Systematic approach to the data and video links emanating from a moving SRM robotic element is shown in Figure 3-34. The format of the up-down link data communication between the Multiplexing Unit and the moving robotic element may be a continuous stream of self-clocking Manchester Biphase at less than 100 KBPS. A low data rate is assumed because of low throughput requirements for the task oriented robotic microprocessor. The video link for the CCTV shall be a limited FM unless eventually a digitized CCD camera approach is used. But regardless of the approach, the video link may require a bandwidth higher than 100 MHz which may be too excessive for the emissive section of the link.

3.2.8.6 Relevant Technologies. Many of the space-oriented technologies that are presently in development or prototype stages will be fully developed and reliably useful by the year 1990. The automation and its control in the early Space Station discussed previously, has several technological areas that are presently state-of-the-art and may require an additional consideration before final decision for their application in Space Station is made. Driving considerations with regard to implementation of the automated elements and their control hardware are: redundancy, reliability, mission safety, radiation hardening, and long life.

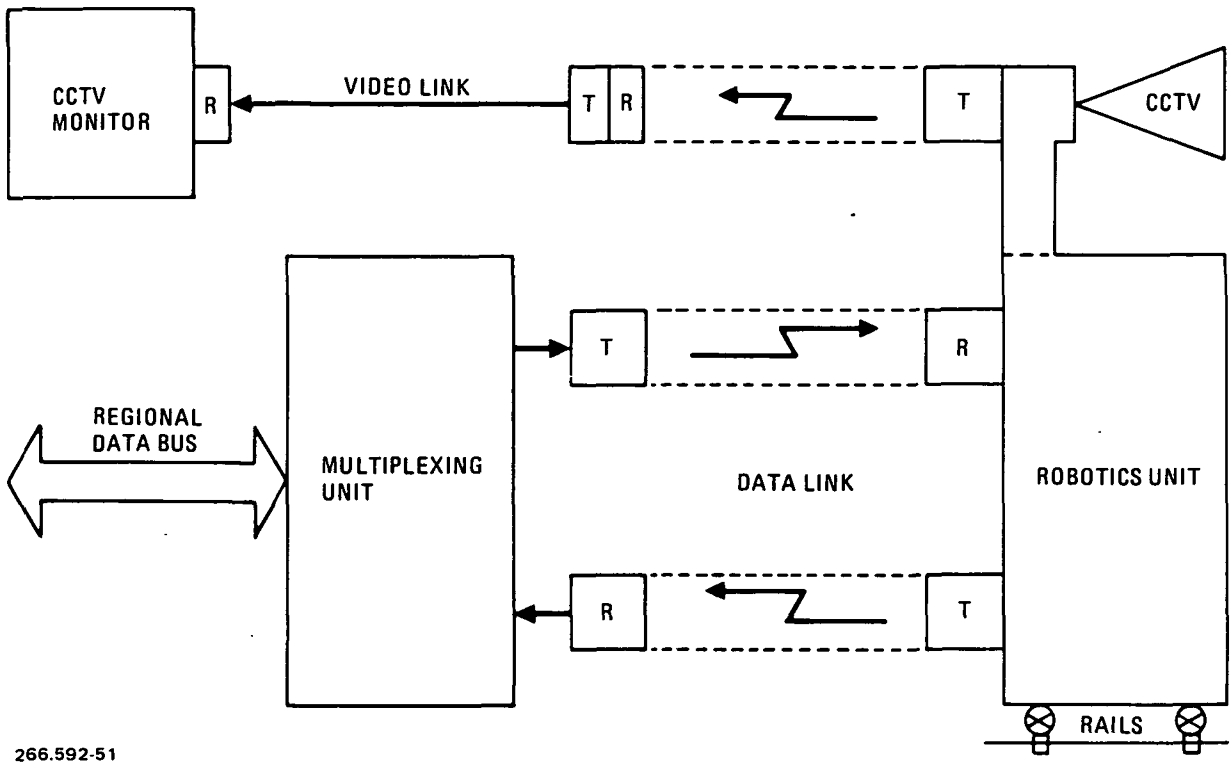


Figure 3-34. Robotics Video and Data Links

General Dynamics Convair Division has designed, developed, and qualified many highly reliable space systems. Specifically, we have designed and implemented a relevant dual failure tolerant and fail-safe control system for the Centaur/Shuttle space missions. Among other major technologies, Convair has developed a highly survivable and radiation hardened optical fiber data link for GLCM control and communication system.

Major electronic and signal processing technologies relevant to the Space Station's automation applications are:

1. Fault Tolerant Computer
2. Error Free Memory System
3. Solid State TV Imaging
4. Infrared Data Command Link
5. Robots Emissive Video Link
6. Fail Safe Redundant Control Subsystem
7. Docking Sensors

With regard to the first two items, NASA is now developing a space qualified computer with a dual redundancy and fault tolerant memory system (reference 7). The solid state imaging technology is now used in TV camera systems and is applicable to the Space Station.

3.2.8.6.1 CCD imaging processing for rendezvous and docking. The SCE docking sensors may use a charge coupled imaging array detector (reference 8). The detector is a buried-channel, line-transfer, charge-coupled device (CCD), with vertical and horizontal picture elements. A typical detector contains 488 vertical by 380 horizontal picture elements within an active image area of 8.8 mm by 11.4 mm. The detector is cooled to an operating temperature below 0C.

The detector array is readout with high speed microprogrammable logic. A micro-processor is employed to compute the location of the centroid of the contact images to an accuracy of about 1/10 of the inter-pixel distance, and to provide sequencing and control functions. The CCD unit possesses some distinct advantages over other types of docking sensors. Those are: 1) the ability to track multiple light sources simultaneously, 2) no sensitivity to magnetic fields, and 3) improved accuracy.

3.2.8.6.2 Docking and cradling. Docking sensors determine the angular difference between the sensor line of sight and the target position. This angular difference, after being measured by the microprocessor, is used to drive a pointing mechanism to align the sensor line of sight to the target position on the space service station cradle. The CCD image signals are processed to synthesize angular error signal and to derive the required change in the approach of OTV to the station's cradle. This implementation may require further study with respect to dynamics of the two systems trying to link with each other physically.

3.2.8.6.3 Infrared communication link. A problem of communicating data and video informations between the moving RMS and the stationary data multiplexing or the CCTV monitoring unit (see Figure 3-34) may be solved by use of infrared devices presently in development by NASA for intercom system within the Orbiter (reference 9). The approach may be directly applicable to the RMS data link with a recommended operation at 100 KBPS.

The wide band video link may require further analysis relative to optical emission approach. In this case, IR emission for high fidelity digitized video signals may not be adequate.

3.2.8.7 Technological Needs. The Space Station automation and control can be implemented without major technological inventions. Present developments in electronics, optics, and the advent of reliable microprocessing subsystems have made it possible to recommend levels of automation that previously would have been too costly.

Further studies of automation and control should concentrate in the area of specific systems problems and their modeling. There is definitely a need to define the data and video signaling approach used between the moving robotic elements and their remote command and monitoring facilities.

At this time, it appears that derivatives from the Shuttle RMS will provide the base for Space Station manipulators.

The following areas are identified for further development:

a. Dextrous capability - for small intricate tasks.

b. Photogrammetric or proximity devices - to accurately determine relative positions and rates for automatic or adaptive operations.

c. Self-contained system - independent of a centralized computer.

d. Moving base capability - power/signal transfer to RMS.

3.2.8.8 Summary and Recommendations. Having established a need for automation in various activities within the Space Station and specifically the use of RMS to service OTV, TMS or the FFS, a control architecture that is safe, reliable and compatible with the overall Space Station's data management system is recommended. Some of the features of this architecture shall be as follows:

a. Failure tolerant redundancy for hazardous and critical functions

b. Ultimate control of all automated elements resides with the Space Station

c. Hierarchical and task oriented RMS control (reference 10) is used for maximum programming flexibility

d. Automation control is exercised by the Station specialist program and a regional data bus

e. Emissive Infrared Data Link is used to provide communication between a moving robotic RMS and its regional multiplexing unit

f. Optical Fiber carries digitized CCTV signals from the RMS work place to the Station's video monitor

3.3 SUPPORT OPERATIONS AND FACILITY REQUIREMENTS

The support of a permanently manned Space Station has major implications with respect to the impacts on the Space Transportation System (STS) and ground support facilities and operations. This subsection presents the analysis of these implications and identifies needs for new STS elements and new ground support facilities.

3.3.1 STS AND LOGISTICS. The Shuttle is the physical link between Earth and the Space Station in low earth orbit (LEO). It will be used to transport all loads going up into earth orbit or beyond, and back to the ground.

The objective of this section is to identify and quantify the total load placed on the Shuttle system in the decade beginning in 1990. That is, the number of Shuttle flights required to transfer the loads generated in the following four categories during this 10 year period:

a. Station build-up

b. Mission emplacement

c. Logistics

d. Retrieval

3.3.1.1 Station Build-up. Station build-up refers to the initial assembly of the station core and emplacement of other elements and equipment that become a permanent part of the Space Station. The station will be assembled at a 28.5-degree, 400 km orbit. The Shuttle will transport the required materials and equipment and directly emplace them using its Remote Manipulator System (RMS). Initially, the station will consist of modules for power generation, crew habitation and crew logistics equipment. Station build-up will begin in 1990. The station will also become habitable in this year. Other modules will then be added for mission support, passageways, and more habitat, power, logistics, etc., as required.

The most rapid growth for the Space Station will occur during its initial assembly in 1990. After that, growth will be gradual to support additional crew members and missions. In about 1994, there will be another period of rapid growth as OTV facilities will be added. Toward the end of the decade, station growth declines.

All major elements of the Space Station have been identified and an estimate has been made of their size and weight. Most elements are large and require a dedicated Shuttle flight to be emplaced. However, there are some smaller items, such as a portable airlock, which are allocated a percentage of the space available in the Shuttle bay.

3.3.1.2 Mission Emplacement. Mission emplacement is the initial transporting and placement of mission equipment in a specified location. The mission may be attached to the Space Station, or it could be a free flyer. From an STS standpoint, there are three basic locations for mission delivery. These are the low earth orbits of 28.5-, 57-, and 90-degree inclinations. For missions going to 57 degrees or 90 degrees, the Shuttle will directly emplace them or emplace them with the assistance of the Teleoperator Maneuvering System (TMS) over the entire decade.

Missions going to 28.5 degrees will be handled in different ways depending on whether the OTV is in operation. IOC date for the OTV is in 1994. For the entire decade, any missions that are to be attached to the Space Station will be flown there directly by the Shuttle. In the period 1990-1993, free flying missions that remain in low orbit will also be directly emplaced by the Shuttle. Those that go to higher orbits, such as GEO, or those that must escape the Earth's orbit, will require some type of booster vehicle and be launched from the Shuttle. Starting in 1994, all missions with final destinations of GEO, 28.5 degrees at a high orbit or escape will be taken initially to the Space Station. From there, the OTV will transport them to the required locations. This eliminates the requirement for booster vehicles and results in a huge weight savings for the STS.

All of the planned missions have been defined in terms of mass and most have been assigned dimensions in the Missions Requirements Data Base (reference 13). Since, in most cases, Shuttle loading is volume limited, dimensions had to be calculated where they were not known. This was accomplished by calculating densities for missions with known masses and volumes by category (e.g., Astrophysics, Earth and Planetary Exploration, Environmental Observations, etc.). These densities were then applied to the masses with unknown dimensions to derive a volume. Depending on the size, weight, pressurization requirements and function of the mission, it was determined whether the mission would be transported in a module or directly in the orbiter bay.

Large volumes (generally over 50 m^3) were designated to be loaded directly in the Shuttle bay. They were assigned a nominal height and width of 4.5 m (to fit in the Shuttle bay) and the length was then calculated. Smaller volumes were simply given cubic dimensions. Missions that were less than about 1000 kg and 15 m^3 were assigned to be transported in a module if they were destined for the Space Station. Missions larger than that, or those not going to or through the Space Station, were designated to be loaded into the Shuttle bay. To each mission mass was added the mass for the transportation module or pallets, as required. Each mission was then converted to a fraction representing how much of a transportation module or the Shuttle bay that it occupied. These fractions could then be added to determine equivalent Shuttle loads.

3.3.1.3 Logistics. The category of logistics includes service, spares and resupplies to missions and crew members, and configuration change equipment. A standard logistics module, similar to that defined in reference 14, will be used to transport logistics supplies. There will be a standard logistics package to support crew members and the Space Station, depending on the number of crew persons on board at a given time. It will include food, water, clothing, air, spares, cryogens, and fuels, among other things. Support of free flyers will consist of spares, cryogens, service equipment, fuel for the OTV or TMS (when applicable), and other consumables. Logistics modules will also take back to earth waste, replaced equipment, and materials.

A fully loaded logistic module can carry enough supplies and equipment to support an 8-man crew for 90 days. The load under these circumstances is about 10,000 kg stored in a total available storage space of 35 m^3. For purposes of calculating the number of logistic modules required, it was assumed that all logistic loads had about the same density as the standard logistic package. That is, a maximum of 10,000 kg could be packed into the available 35 m^3 of storage space. Using this assumption, the service masses for the various missions can be converted to volumes and added together, along with missions volumes, to fill the logistic modules. Two logistic modules were assumed to be the equivalent of one Space Shuttle load.

In many cases, missions would call out a service at certain intervals, but not specify a mass for that service. When this occurred, an estimate was made using a summary of NASA payloads (reference 15). This gave the payload masses of numerous seven-day Shuttle missions, and the consumables and equipment used up in the course of each flight. Missions in this summary were matched to categories in the Mission Requirements Data Base (reference 14). A percentage of consumables to initial mission mass was calculated for the one week missions and then multiplied by the initial masses for the planned Space Station mission for each category. This number was then multiplied by the weeks between service and finally by 75 percent to take into account the greater efficiency that should be built into a longer mission. The resulting figure was used for the service mass and figured into the Shuttle loading as described previously.

3.3.1.4 Retrieval. This is exactly what it sounds like; return of a mission to earth when it has been completed. For the sake of simplicity, the return mass of a mission was assumed to be the same as when it was emplaced. Logistic masses were also returned, but only 65 percent of what was sent up. This

figure was reached by evaluating the contents of a standard logistics module. Part of the mass was propellant, which was completely consumed. Assuming 95 percent of the remainder was returned, this resulted in the net return of 65 percent of the logistics mass sent up. Retrieval is only a secondary problem for the STS. In all years, there are more shuttle loads of equipment going up than returning to earth. Therefore, there is always adequate capability to transport returning loads.

3.3.1.5 Summary. The results of the STS traffic analysis are summarized in Figure 3-35. The bar chart shows the equivalent STS flights required between 1990 and 2000. It excludes the propellant requirements for the OTV, which are discussed in another section. However, all station build-up items, mission emplacements and services as described in subsections 3.3.1.2 and 3.3.1.3, are included.

The majority of the Shuttle flights represented go to 28.5-degree LEO, including those carrying GEO and escape missions that are launched to their final destinations from LEO. The only shuttle flights that go to other orbits are those represented by the light portion at the top of each bar. These loads go to 57- or 90-degree inclination orbits.

The years of heaviest Shuttle traffic are 1992-1995. There are several factors driving this. One factor is the bulk of the expendable launch vehicles

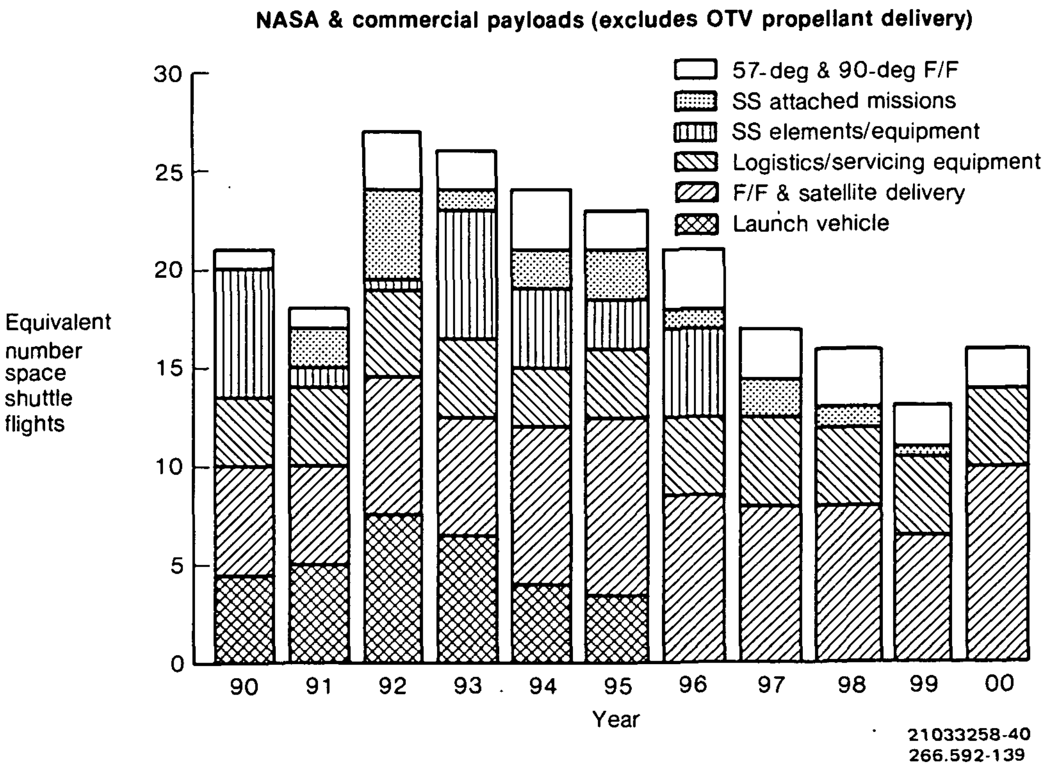


Figure 3-35. STS Shuttle Traffic Summary

vehicles required to emplace GEO and escape missions, a factor which also affects the 1990-91 traffic. In 1994 and 1995, the OTV is phased in, reducing and finally eliminating the expendable vehicles in 1996. Another contributor, especially in 1993 and 1994 is the increased activity due to build-up at the station to support the OTV capability. Another big building year is 1996, necessary to expand the OTV support capability.

The first year of the Space Station shows moderate Shuttle traffic. Not many satellites are launched, or other missions emplaced. However, there are quite a number of flights dedicated to the build-up of the Space Station itself. Also, some of the Space Station modules going up at this time will already have missions mounted in them, so there are actually some Space Station attached missions going up, not shown on the chart. In the last half of the decade, shuttle traffic drops off as station build-up ceases and mission emplacements become fewer.

The equivalent shuttle loading appears to be in line with the expected STS capabilities for the decade beginning in 1990. However, it should be kept in mind that the totals presented here do not include the DOD requirements. These should be included and evaluated to determine whether or not more orbiters are required.

3.3.2 GROUND SUPPORT OPERATIONS. Ground support operations for the Space Station program involves the Planning/Organizational phase of the program as well as the Functional or Operational Phase.

3.3.2.1 Planning and Organization. The primary management objective in the planning and organizational phase of ground support operations is to provide concepts for cost-efficient and functionally effective prelaunch, launch, and on-orbit ground operations in support of space station elements and payloads. To be effective, these concepts must

a. Be compatible with existing (1990-2000) STS operational procedures, schedules and facilities.

b. Minimize requirements for new technology.

c. Minimize requirements for additional facilities and procedures.

d. Minimize changes to existing facilities and procedures.

e. Minimize schedule risks.

f. Provide maximum probability of mission success by minimizing technical and handling risks.

g. Simplify hardware flow, configuration control, communications, and problem solving.

Optimum solutions for these issues are obvious in some cases, complex in others, and dependent on eventual program institutional and organizational decisions in others. Location of prelaunch and launch facilities for example,

should obviously be assigned to existing KSC and VAFB locations. Configuration control and operational problem-solving, however, are functions with locations that are tradeable and will ultimately depend on institutional arrangements and responsibilities.

3.3.2.2 Ground Operations Management. The objective of ground operations management will be to establish and implement a ground support operations plan that will ensure functional capability; maintain safety, reliability and efficiency goals; and provide operational flexibility on a non-interference-with-schedule basis.

Regardless of institutional issues and allocation of responsibilities between industry, the government, and possible new operations authorities, a clear division of management responsibilities between pure Space Station functions and STS-related Space Station functions appears advantageous, from both organizational and location standpoints. Such a division is shown in Figure 3-36. Space Station ground functions would be the responsibility of a designated Space Station Center, with location to be determined, and STS-related operational functions would be the responsibility of the two existing launch facilities at Kennedy Space Center (KSC) in Florida and Vandenberg Air Force Base (VAFB) in California.

3.3.2.3 Space Station Center Facilities. The NASA Space Station Operations Working Group has stated that "Ground system simulation shall be required to support on-board problem resolution." Carrying this basic guideline a step further, colocation of simulation facilities for problem solving, together with a configuration control center and a mission support center with communications capabilty, would appear logical and functionally efficient. These functions and facilities would comprise a "Space Station Ground Function." The Space Station Center would include an Integration Facility and an Operational Management Facility.

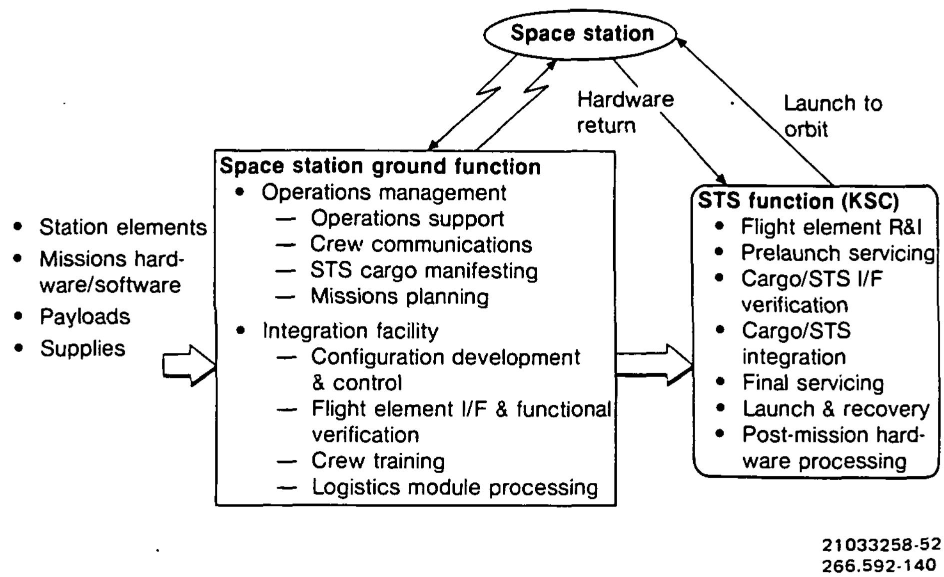


Figure 3-36. Space Station Ground Support Activities

Space Station Integration Facility. Ground support functions at the Integration Facility would include the following:

a. Space Station configuration development in the program development phase, leading to establishment of a Space Station ground article (simulator, mockup, or hangar queen) for software and hardware configuration control during the Initial Buildup Phase and during the Operational Phase of the program.

b. Receipt of flight-article Space Station elements for form, fit, and function check, including Space Station interface compatibility, systems function, and functional compatibility with TDRSS, STS, and ground control.

c. Receipt of payload mission hardware for form, fit, and functional check compatibility with the Space Station.

d. Compatibility check of follow-on Space Station mods, deletions, and additions.

e. Space Station crew training.

f. Logistics module processing.

To minimize ground transportation costs and schedule delays, all Space Station elements and payloads are assumed to first undergo developmental and acceptance testing at the manufacturers' facilities for configuration and function, before delivery to the Integration Facility.

At the Integration Facility, all elements and payloads would undergo simplified functional verification, overall system compatibility validation, and configuration compatibility validation before transfer to the STS launch sites for Shuttle integration and launch. Without proper configuration control as provided by the SSIF or equivalent, serious on-orbit integration problems could develop resulting in schedule delays, interference with mission objectives, possible damage to station system and mission hardware, and increased costs associated with on-orbit fixes and replacement hardware transportation to orbit.

Operational Management Facility (OMF). The OMF would include Space Station status monitoring, operational communications with the Space Station, problem solving support in conjunction with the Integration Facility, and other mission support functions including missions planning and STS cargo manifesting. Responsibility and authority for these functions would be separate and distinct from STS mission control functions, with interface coordination to be determined as the program develops. Ground control functions would also tend toward on-orbit Space Station control and autonomy wherever possible, to minimize ground segment costs.

Data Processing & Dissemination. There is little doubt that mission effectiveness may well take a quantum jump as a result of manned operations on the Space Station, particularly in the realm of on-the-spot observation, manipulation, calibration and control of scientific experiments and observations. On-board data acquisition and analysis will be of inestimable value in many

cases. In others, data accumulation need only be transmitted to an earth terminal for reduction and dissemination to the concerned agencies and users. Mission requirements will be refined and expanded as the program develops, and tradeoffs will identify the most efficient ratio of on-board data processing to ground processing, and its impact on communications traffic requirements. In any case, there will be an obvious need for a ground data processing facility of some magnitude for reception, analysis and/or reduction, and dissemination to the concerned mission sponsors. Further study may indicate the advisability of multiple ground receiving stations to expedite dissemination of mission results, but a central data facility appears essential for Space Station program control and documentation.

3.3.2.4 Launch Sites. Kennedy Space Center in Florida and Vandenberg Air Force Base in California are assumed to be the two STS launch sites in the Space Station era. These facilities and their management functions will be responsible for all payload processing at the launch site, and integration with the STS in preparation for launch to orbit. They would not be responsible for the proper configuration of the Space Station, its on-orbit functions, or its on-orbit ground support functions. These would be the responsibilities of the Space Station Center as previously discussed, unless the Center were located at one of the launch sites.

Ground support facilities at the two launch sites will differ markedly, but the basic functions will be identical. For simplicity, only the KSC ground operations are discussed here. Flow paths and facilities involving the payloads are shown in Figure 3-37.

A basic objective of STS ground operations is to ensure minimum turnaround time for the Orbiter. To attain this goal, KSC operations are separated into three distinct hardware flow paths -- payload processing, off-line operations, and on-line (Orbiter) operations.

Payload Processing Facilities (PPFs). These are facilities used for payload receiving and inspection, assembly, testing, and checkout after delivery from the manufacturer (or from the Space Station Center in the case of Space Station elements and payloads). Most of the PPFs are hangars, clean-rated assembly buildings, or special facilities located at Cape Canaveral Air Force Station (CCAFS) adjacent to KSC, or located directly on KSC property. At these payload processing facilities, unit payloads are given a simple receiving/inspection and functional check as needed. More complex payloads may also be assembled, given a complete integrated systems check, and loaded with required consumables and propellants at facilities such as ESA-60A (Explosive Safe Area), the Delta Spin Test Facility, or the Titan Solid Motor Assembly Building (SMAB). After processing, the payloads are delivered to one of the "off-line" integration facilities.

Off-Line Operations. (This is the path that all other supporting elements of the STS take before joining with the Orbiter, i.e., the Solid Rocket Boosters, the External Tank, and the integrated cargo. We are concerned here only with the integrated cargo.)

After clearing the PPFs, payloads are ready to be integrated as a single cargo for the STS Orbiter. To ensure compatibility of payload hardware and software

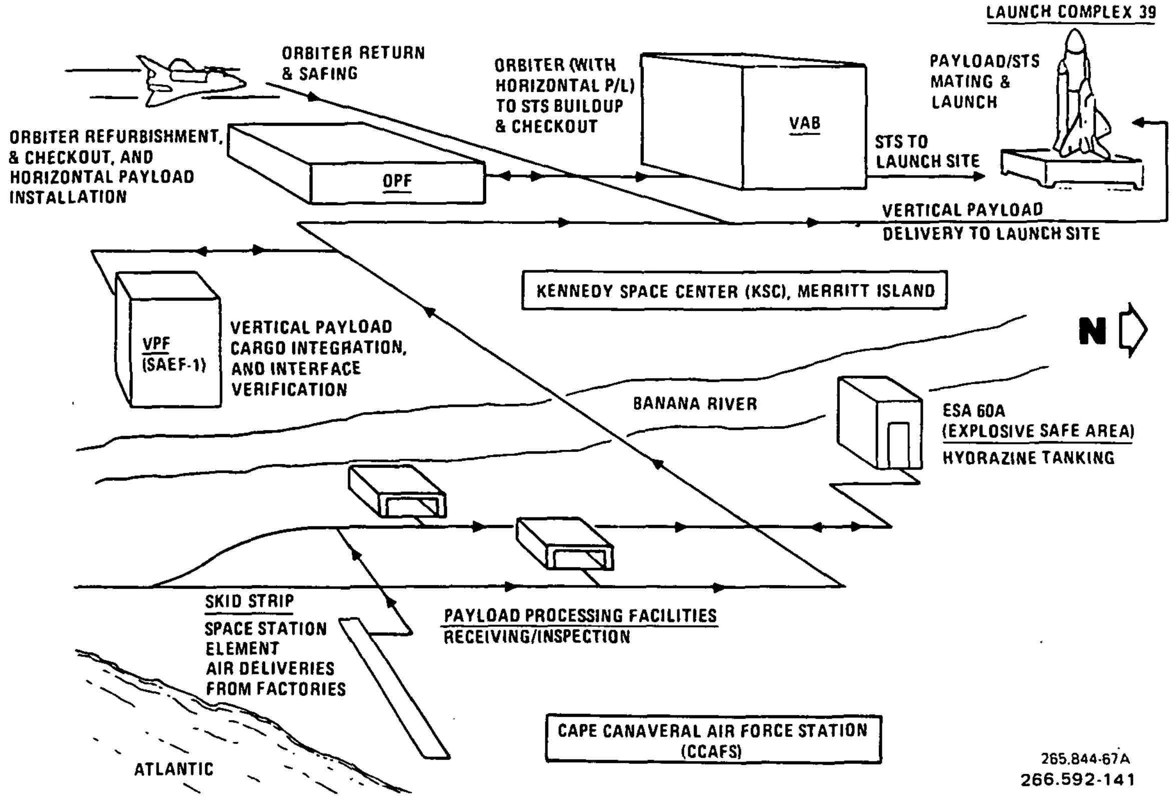


Figure 3-37. Ground Operations at KSC

with the Orbiter, Cargo Integration Test Equipment (CITE) is used to simulate Orbiter interfaces and procedures. CITE objectives are to:

a. Protect on-line operations from mission-peculiar problems.

b. Integrate (unify) the assigned payloads as a single Orbiter cargo, prior to entering the Orbiter ground operations flow.

c. Verify, where possible, all payload/Orbiter/Launch Processing System interfaces.

CITE testing is accomplished in one of two Off-line Cargo Integration Facilities, dependent on whether the cargo is categorized as either horizontal or vertical.

Horizontal Payloads. If a Space Station payload is passive, structural, palletized horizontally, innocuous with respect to consumables, insensitive to attitude, or carries no propellants or solid rocket motors (with some exceptions), it can be treated as a horizontal payload. The O&C building in the industrial complex at KSC is the Off-line Integration Facility for all such payloads. After integration and interface compatibility (CITE) testing are complete, the unitized cargo is transported in a horizontal canister to the Orbiter Processing Facility (OPF) to enter the "On-line" Orbiter processing flow and be installed in the Orbiter.

Vertical Payloads. Any Space Station payload that requires maintenance of a vertical attitude during prelaunch ground operations and installation in the Orbiter, or that carries propellants, noxious consumables, or solid rocket motors, will be classified as a vertical payload and will undergo CITE procedures in the Vertical Processing Facility (VPF), a safe area. After completion of cargo integration and cargo/Orbiter/LPS interface testing and validation, the Space Station payload will be transported in a vertical canister to the launch complex for installation in the STS Orbiter cargo bay.

On-Line Operations. This is the path that the Orbiter takes from landing to liftoff. It includes the landing strip, the Orbiter Processing Facility (OPF), the Vertical Assembly Building (VAB), and Crawler transport on the Mobile Launch Platform (MLP) to Launch Complex 39.

A Space Station horizontal payload enters On-line operations at the OPF, where it is installed in the Orbiter cargo bay. It stays in the Orbiter as the Orbiter goes to the VAB, is lifted and mated to the other elements of the Shuttle stack on the MLP, and is transported to the launch site on the crawler for final hazardous servicing, countdown preps, and launch.

A Space Station vertical payload enters the On-line operations path at the launch site, where it is transferred from its canister to the Rotating Service Structure (RSS) and installed in the Orbiter.

3.3.2.5 Timelines. The current Shuttle Turnaround Analysis Report (STAR 024, November 1982) provides a complete breakout of timeline allocations for both horizontal and vertical payloads, and assessment of two typical payloads the Spacelab (horizontal) and the TDRS/IUS (vertical). Results of the report are summarized in Figure 3-38, showing payload involvement in On-line operations.

The operational phase of the STS is in its infancy, and at the beginning of a learning curve. Hence, the marked difference between the ideal (14 day) Orbiter turnaround time and the currently projected (37.5 day) turnaround time. As the program matures, the actual turnaround period will undoubtedly decrease to an as yet unknown "normal" turnaround time. Nevertheless, the differential has caused the Cargo Community some unforeseen problems, having designed their gas and electrical storage systems for much shorter on-line operations times than presently projected. This has resulted in requests for late pad access to the Orbiter cargo bay for system reservicing. In the Space Station era, Orbiter turnaround times should be well established, and will influence but not be a problem to designed payload system capabilities.

Of greater significance is the differential between horizontal and vertical payload stay times in the Orbiter cargo bay, before launch. Space Station element and mission payload designers should be well aware of the advantages and disadvantages of designing for horizontal or vertical installation in the Orbiter. Horizontal installation may be a convenience advantage for many payloads, but the penalty in on-line time in the Orbiter cargo bay is readily apparent in Figure 3-38: eight days for horizontal payloads versus one day for vertical payloads in the ideal case, 25 days versus 12.5 days in the currently projected assessment. To design efficiently yet minimize the possibility of ground operations problems due to stay time in the Orbiter cargo bay, payload designers are well-advised to stay current in their knowledge of payload ground operations and their design constraints.

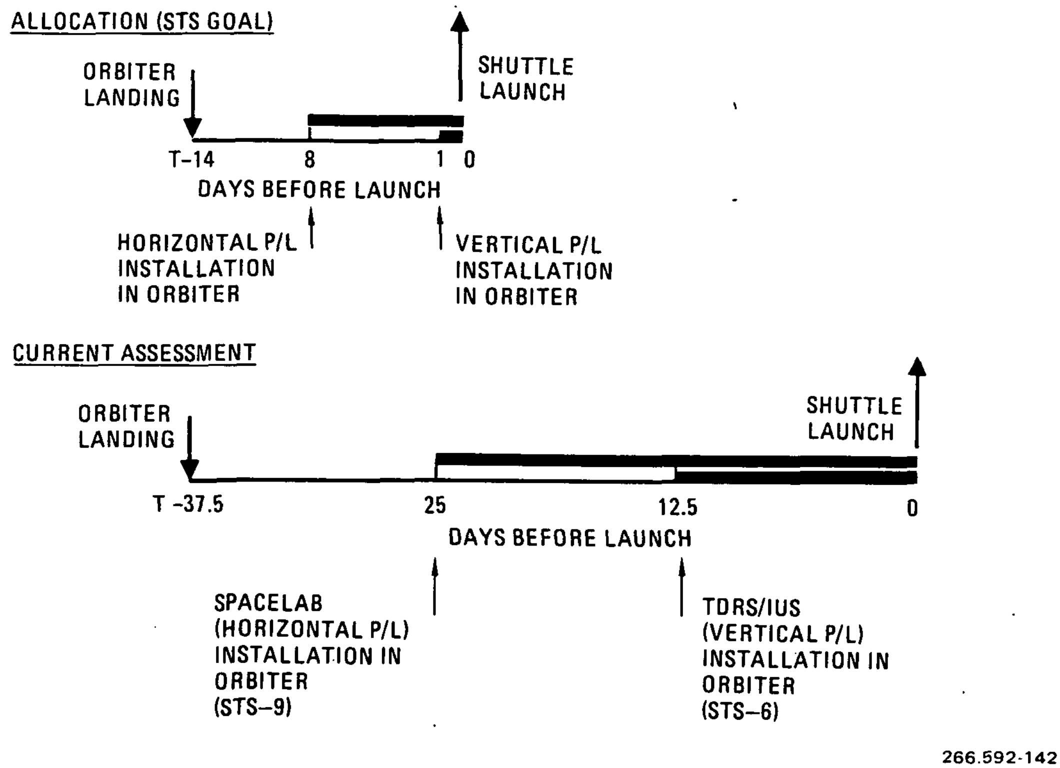


Figure 3-38. On-Line Time for STS Payloads

3.3.3 PROPELLANT TRANSPORTATION TO LEO. Propellant required to support Space Station operations can be broken down into three basic categories: OTV propellant, TMS propellant, and Space Station orbit maintenance and attitude control propellant. Propellant requirements are summarized in Table 3-26.

Table 3-26. Basic Propellant Requirements

CATEGORY	PROPELLANT TYPE	AMOUNT REQUIRED PER YEAR (k lbw)	AMOUNT REQUIRED PER YEAR (ft.^{3})
OTV	O_2/H_2 (6:1)	400-700	19,000-33,000
TMS	MMH	40-80	750-1,500
Space Station-OTV Maintenance*	O_2/H_2 (6:1), or MMH	3-8	140-380
Attitude Control	MMH	2-4	40-80

*Including Stationkeeping

It is clear that propellant delivery requirements are primarily governed by the LEO/GEO transportation requirements, not by Space Station orbit maintenance or attitude control concerns. The figures for OTV and TMS propellant are drawn from the mission requirements described in subsection 2.2.1 and 2.2.2.

3.3.3.1 Cryogenic Propellant Delivery. Of the two propellant types, cryogens and storables, the cryogens are the major issue due to the large volume requirements of the very low density LH_2. A variety of cryogenic propellant delivery options were examined as candidates for further study. Previous studies have indicated the high sensitivity of Space-Based OTV costs to LEO propellant delivery costs. In a comparison with ground-based single-use upper stages such as Centaur, a Space Based system will only start to show a benefit when bulk propellant delivery costs drop to about half of the standard shuttle payload delivery cost (about 1,200 $/lb in 1983$). Figure 3-39 shows a comparison of payload costs per lb versus propellant delivery cost per lb. Emphasis was placed on concepts which showed promise of lowering the delivery costs to a fraction of the standard cost. Table 3-27 summarizes the relative merit of a number of propellant delivery concepts. Figure 3-40 illustrates these concepts, together with gross estimates of propellant delivered.

Chief among the concepts examined were those designed to recover residuals in the External Tank. At MECO the External Tank has achieved 98 percent of

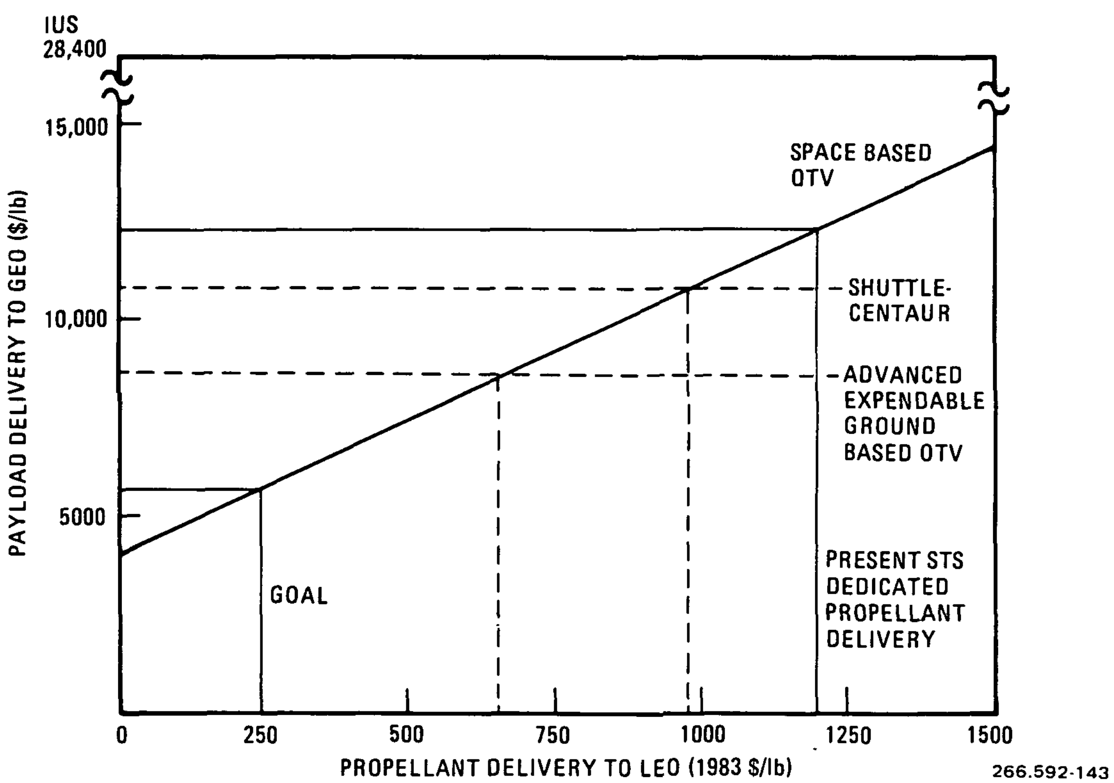


Figure 3-39. Operating Cost Comparison of GEO-Transportation Systems

Table 3-27. Cryogenic Propellant Delivery to LEO-Concept Evaluation

CONCEPT	RATING*								
	ORBITER PAYLOAD RESTRICTIONS		STS EQUIPMENT MODIFICATIONS REQUIRED		IMPACT ON LAUNCH** SERVICES	ORBITAL FACILITIES REQUIRED	OPERATIONAL RELIABILITY & COMPLEXITY	PROPELLANT DELIVERY COST/LB	TOTAL
	LENGTH	WEIGHT	ORBITER	ET					
ET SCAVANGING CONCEPTS									
(1) ORBITER PAYLOAD BAY TANKS	1	1	4	3	4	4	4	1	22
(2) ORBITER MIDFUSELAGE TANKS	4	2	3	3	3	3	3	3	24
(3) ORBITER WING TIP TANKS	4	1	1	2	1	3	1	2	15
(4) AFT CARGO CARRIER TANKS	4	3	4	2	3	4	3	4	27
(5) OTV RESIDUAL RECOVERY	4	4	4	2	4	4	2	4	28
OTHER ORBITER CONCEPTS									
(6) DEDICATED PAYLOAD BAY TANKS	1	1	4	3	4	4	4	1	22
(7) MIDFUSELAGE H_2O TANKS	4	3	3	4	3	1	4	3	25
HEAVY LIFT LAUNCH VEHICLES									
(8) ET TANKER	–	–	1	4	4	3	4	4	20
(9) DEDICATED SEPARATE TANKS	–	–	1	4	3	4	2	4	18

*WORST 1 2 3 4 BEST

**NO. OF FLIGHTS REQUIRED AND GROUND MODIFICATIONS TO EQUIPMENT/PROCEDURES REQUIRED

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orbital velocity with expected minimal residuals of 9,380 lb with a full payload. With average manifesting efficiency, less than the maximum payload weight will be lofted and therefore ET residuals could be expected to rise to as much as 25,600 lb for a nominal mission.

Of the five ET scavenging concepts considered, the OTV Residual Recovery or "Honeybee" concept was selected for further study. Concept 4 which places residual catch tanks below the ET and possibly uses these tanks directly on an OTV comes very close to the Honeybee and also needs further study. In question is the weight and cost penalty for propellant tanks able to withstand the severe thermal and acoustic environment at the aft end of the ET. Primary advantage of Concept 1 is simplicity of design and operation. Our analysis indicates that most STS missions will be volume-limited, not weight-limited, and the practical utility of any concept which restricts payload bay length is therefore questioned. Concept 2 overcomes this last deficiency at the expense of operational simplicity by placing residual catch tanks below the payload bay between the frame elements. Volume restrictions between the frames may limit the amount of residuals which might be recovered.

Other concepts, which do not rely on ET scavenging to deliver cryogens to LEO, include the obvious approach of simply placing propellant tanks in the payload bay and taking up a full load of propellant, about 58,000 lb. A major disadvantage that precludes this concept from consideration as a primary means of propellant delivery is the high cost.

Another concept examined several years ago utilizes the excess payload weight available on most missions to transport 10-25,000 lb of water held in tanks below the payload bay. A large solar array on the Space Station would then power an electrolysis operation to separate the water into hydrogen and oxygen, liquefy them and store them for later use. This concept has several advantages over others in that it takes advantage of the average volume-limited payload and carries up a relatively high density liquid. A disadvantage is in the large on-orbit facilities requirement and the excess oxygen produced (20 percent by weight) beyond requirements by an OTV (operating at a 6:1 mixture ratio). However, the excess could be used as a Space Station environmental consumable.

For the mature OTV traffic model, large quantities of cryogens will be required on orbit and this can only be met by a new Heavy Lift Launch Vehicle. Shuttle derived vehicles which exchange the shuttle orbiter for an unmanned payload capsule hold the most promise. Concept 9 shows this payload capsule configured as propellant tanks. This concept has the advantage that these same tanks could be attached to the Space Station and used directly for propellant supply there. A disadvantage is that these tanks are too large to be returned to earth on the Shuttle and would therefore have to be thrown away, along with the ET, after use.*

*Either of these HLLV concepts can loft about 200,000 to 220,000 lb of propellants while the largest tanks which can be placed in the orbiter will only hold 140,000 lb of O_2/H_2 at a nominal 6:1 mixture ratio.

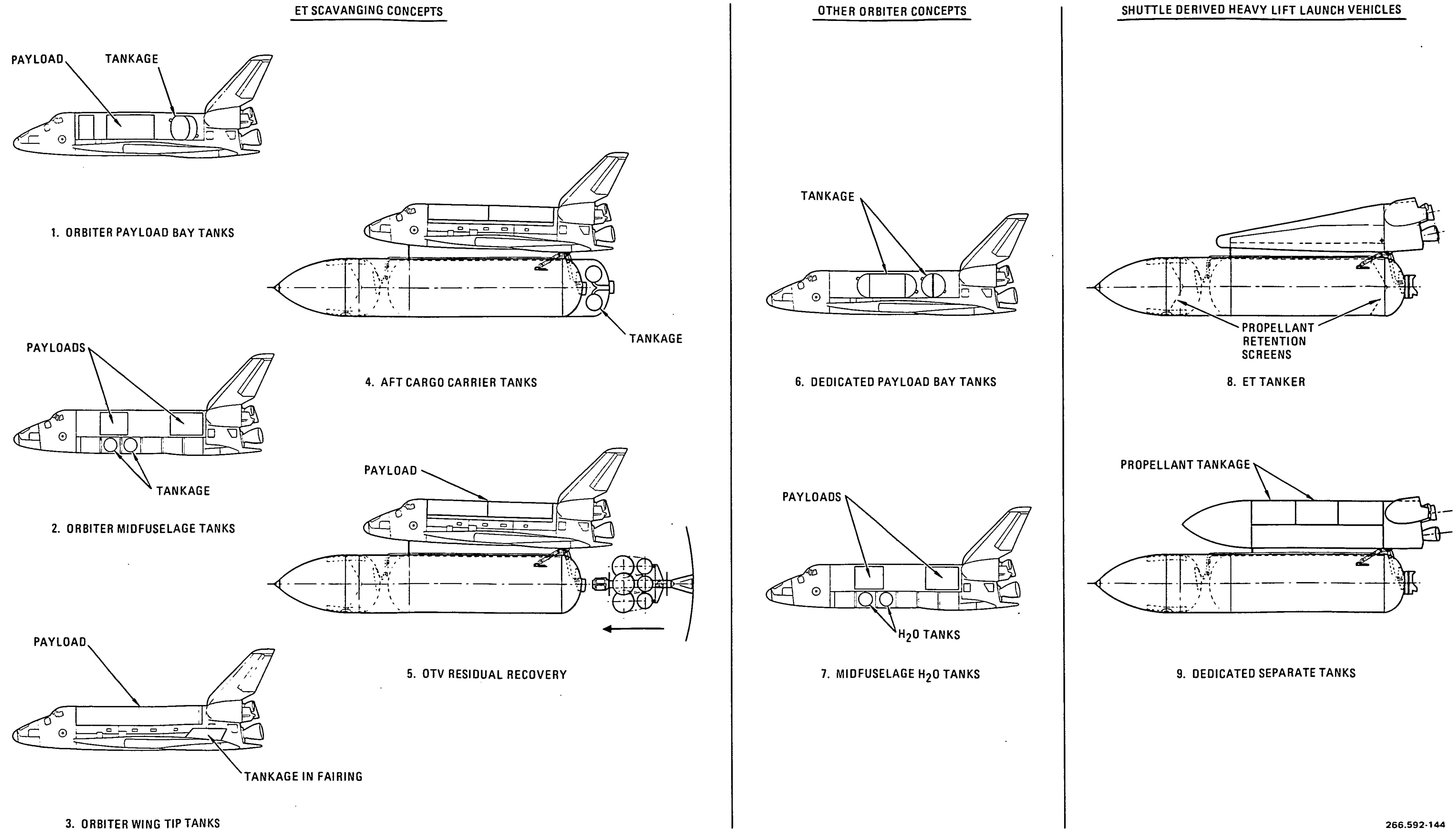

Figure 3-40. Propellant Delivery to LEO Concepts

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Concept 8, chosen for later study, overcomes this disadvantage by leaving the cryogens on the ET and having only an engine pod attached to it. Cryogens are then offloaded from the ET at the Station and the ET disposed of as desired. Advantages include minimal change required to the ET and elimination of the need for a new set of flight qualified cryogenic tanks.

3.3.3.2 Honeybee ET Scavening Concept. The Honeybee concept utilizes the automatic rendezvous and propellant loading/unloading capabilities of the OTV to directly off-load residuals from the ET. The OTVs light weight and high maneuverability are utilized to dock with the ET within 30 minutes of MECO. Boil-off losses, particularly with the LH_2, are therefore minimized without the added complexity and reduced manifesting efficiency inherent with payload bay or Aft Cargo Carrier propellant tank concepts.

Thermodynamic analysis of the Honeybee concept is reviewed in Subsection 3.3.3.3. The analysis indicates that 14,200 lb of usable LO_2/LH_2 can be extracted from the ET on a nominal mission. The OTV utilizes 2,400 lb of its own propellant to recover this and an additional 500 lb is lost through in-flight boiloff from the OTV tanks and during transfer to the Space Station holding tanks. The net profit of propellant per mission is therefore 11,300 lb.

Figure 3-41 illustrates the principal features of the Honeybee Concept. An OTV is launched from the Space Station one and one half to six hours before the Shuttle launch. The OTV (without payload) would follow a transfer orbit to the rendezvous orbit (50 to 100 n.mi.) and rendezvous with the orbiter/ET. Any shuttle flight going to the Space Station and quite a few others going to nearby inclinations would be economically accessible by the OTV. Once the OTV is in the rendezvous orbit, the shuttle ascent trajectory software is updated with the exact orbit parameters. The OTV remains for up to three orbits before STS launch.

After launch, as the STS nears MECO, the OTV tracks the rising stack and begins to compute intercept maneuvers required.

To reduce propellant boiloff, it is desirable to reduce liquid-vapor mixing, which is exacerbated by springback of the aft bulkhead of the ET. Several procedures before and after MECO may prove feasible to reduce liquid-vapor mixing. These include:

a. Deep throttling of the SSMEs to 50 percent.

b. Sequential shut-down of the SSMEs.

c. Intermittent firing of one or two aft facing PRCS engines after MECO until OTV terminal maneuvers.

d. Addition of aft-directed propulsive vents to the ET.

The ET is shown modified with a docking port on the aft end. The docking port has propellant, electrical, and command/data line disconnects, and structural attachments to interface with the OTV. A blow-off cover protects the docking port during ascent. Propellant lines lead directly into the ET H_2 tank and to the ET side of the O_2 interface with the orbiter.

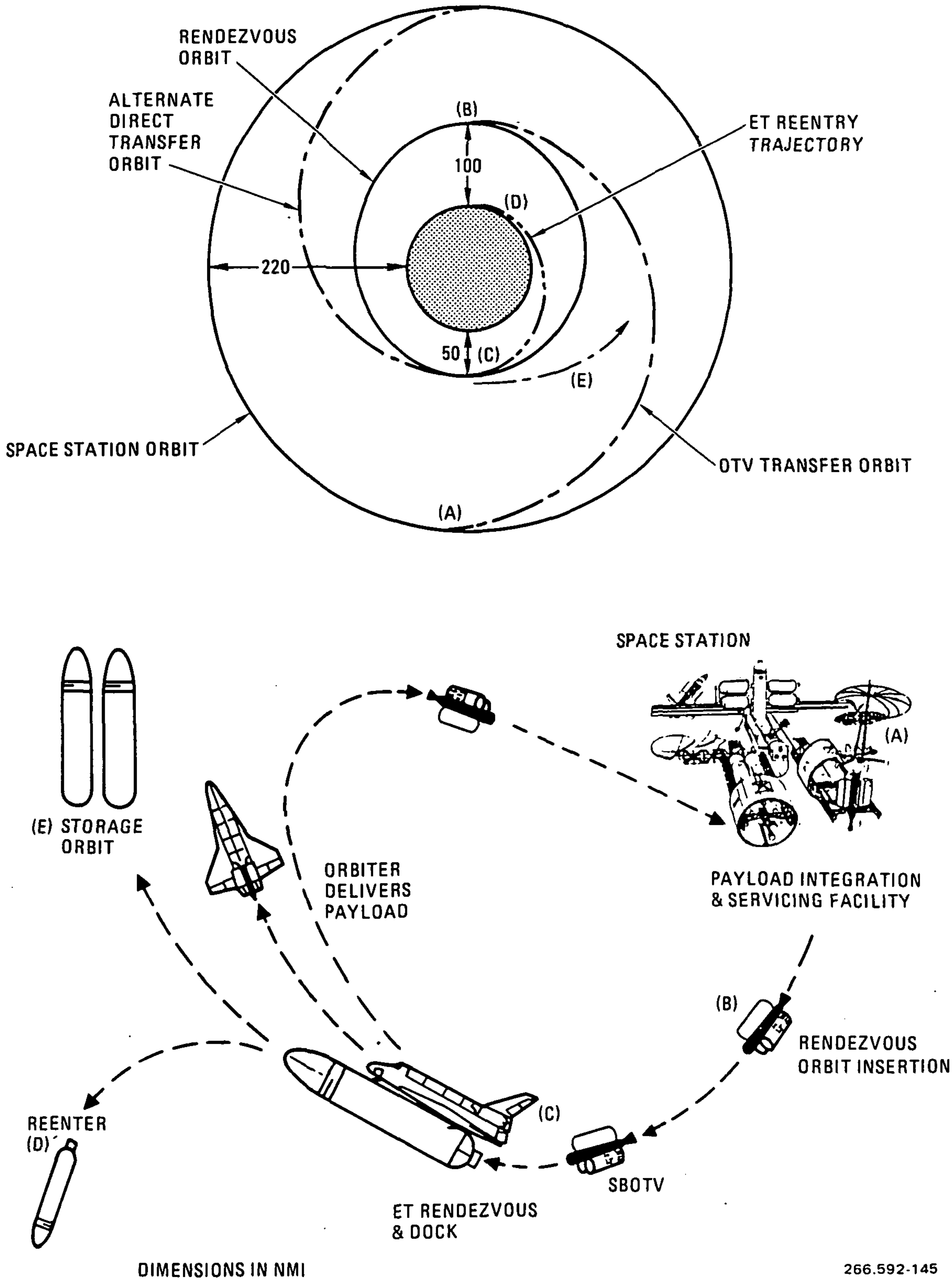

Figure 3-41. Honeybee ET Scavenging Concept Orbit Mechanics

Due to the large amount of O_2 in the orbiter at MECO, it may be economical to also tap the orbiter side of the disconnect. Electrical and command/data lines connect with the ET wiring harness and thence into the orbiter through the existing orbiter disconnect panel.

The Orbiter remains attached to the ET while the OTV, under automatic control, maneuvers to intercept. Under normal operation the OTV would use its automatic rendezvous/docking sensors and G&N computer to perform the docking. During terminal docking maneuvers, the orbiter would have override capability to cancel the docking and separate the OTV from the ET/orbiter. The existing TV camera in the aft ET attachment well of the orbiter is modified for tilt and pan to allow the orbiter crew to monitor the docking operation. In addition, the OTV would have a TV camera to allow crew monitoring of the docking operation. In the event that a hard dock cannot be achieved between the OTV and the ET, the orbiter can inject the ET into a controlled reentry.

The Orbiter disconnects from the ET once verification of an OTV hard dock is received and separates in the standard procedure with PRCS firings. Once safe separation has been achieved the Orbiter crew may elect to remain nearby to monitor the propellant loading operation or may use the OMS engines to proceed to their assigned mission orbit.

The OTV loads the ET residuals with a combination of pressure head caused by firing its main engine and pump head provided by cryogenic pumps on board the OTV. First the OTV aligns itself along the vehicle velocity vector such that the main engine serves to decelerate the ET. The main engine is cycled up to 20 percent thrust and decelerates the ET for 4-5 minutes, imparting a ΔV of 150-200 ft/sec. ET residuals are settled, collected, and pumped into the OTV tanks during this operation. Once all accessible residuals are loaded, the propellant lines are disconnected, the OTV separates and the ET is programmed to tumble in preparation for reentry. The OTV then accelerates into a return transfer orbit to the station.

Preliminary performance analysis indicates a minimum ΔV requirement for the entire OTV operation of 1,390 ft/sec. (from Space Station undock to redock), which consumes 1,770 lb of OTV propellant. With orbit phasing and other intermediate orbit maneuvers to intercept the shuttle, the nominal ΔV for this operation would rise to approximately 1,800 ft/sec, requiring 2,400 lb of OTV propellant. In addition to this propellant requirement, there is also the orbiter RCS propellant requirements, which have not been assessed here.

3.3.3.3 ET Tanker Concept. Large quantities of propellant may be delivered to LEO at low cost with little disruption of other high priority STS traffic with a Shuttle derived Heavy Lift Launch Vehicle (HLLV). The ET Tanker concept avoids the added cost and weight penalties of separate "payload" propellant tanks for the HLLV. For such large propellant quantities, boiloff from the existing External Tank is a minor concern for the 24-hour (maximum) period from MECO to propellant offload into Space Station dewars. The ET Tanker is also compatible with other applications for an HLLV; a cylindrical payload container/fairing may be substituted for the aerodynamic fairing illustrated here. Maximum commonality with Shuttle components assures relatively low development cost. The potential for disassembly of high value subsystems, such as the SSMEs avionics, and others, should reduce operational costs substantially as well.

Preliminary performance analysis of the ET Tanker indicates that 210 - 220,000 lb of usable propellant is available at MECO on a direct ascent to the Space Station. For conservation, a figure of 210,000 pounds is utilized in the thermodynamic analysis which follows in subsection 3.3.3.4.

The ET Tanker is illustrated in Figure 3-42. The External Tank is modified in only two major respects:

a. A berthing system is incorporated into the aft end of the tank for structural attachment to the Space Station. The data and control harness for the ET/Propulsion Module also passes through the berthing system interface. An insulated blowoff cover, which can be removed manually in the event of failure, protects the berthing system during ascent.

b. Conical stiffened bulkheads with multiple capillary screens are added to the O_2 and H_2 tanks, supported from existing ring frames. These bulkheads prevent propellant drift to the forward portions of the tanks, thus maintaining propellant vapor stratification. Maintaining vapor stratification significantly reduces boiloff rates and venting requirements. The bulkheads are made up of stiffened stainless sheet material perforated with 3 to 8 inch diameter holes to which are attached capillary screens. Screen area to total area ratio is about 1:2, so propellant feed during ascent is not affected.

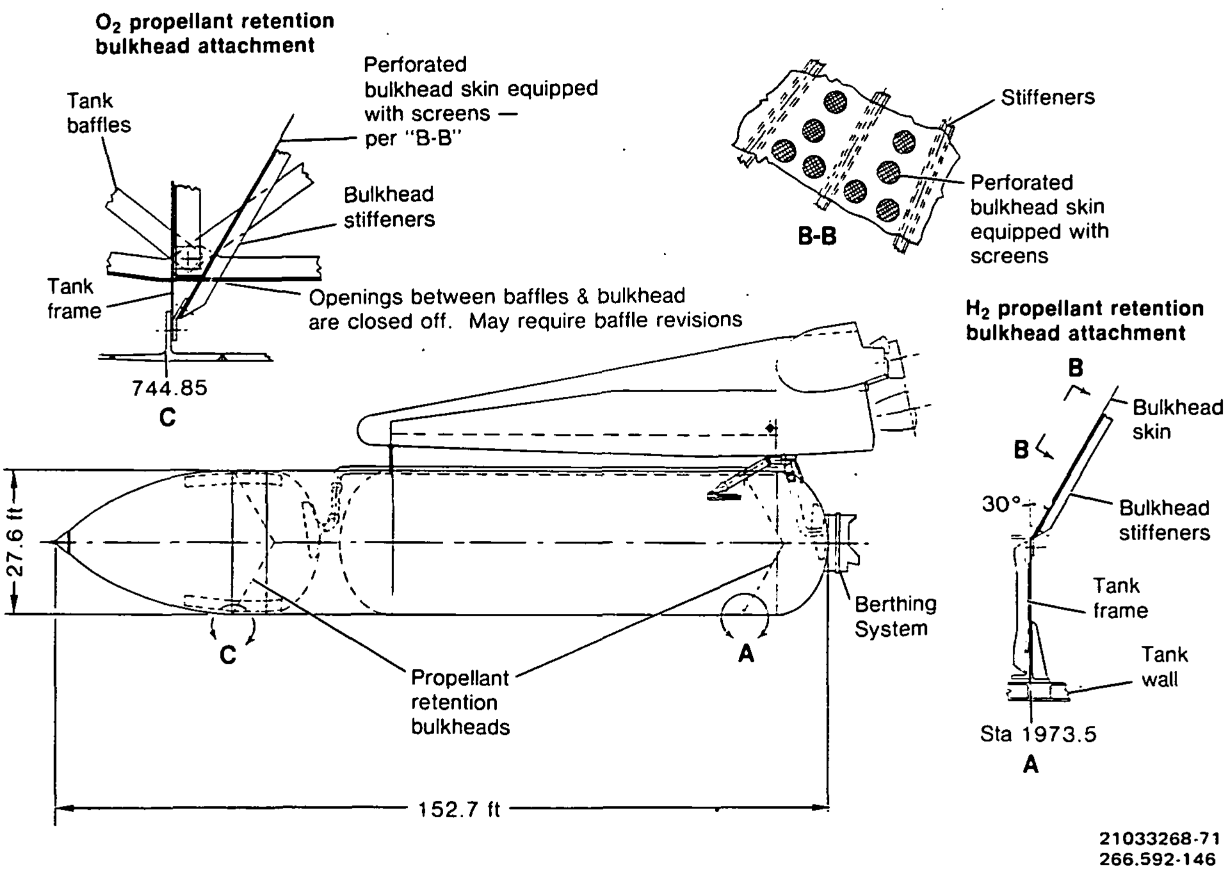

Figure 3-42. ET Tanker Concept

Several different concepts for the propulsion module are feasible. A chief distinction is whether the propulsion module is recovered ballistically or by on-orbit disassembly and Shuttle return of key subassemblies. For high mission models, ballistic recovery tends to show a benefit due to shorter turnaround time, minimized spares requirements and the fact that the entire propulsion module is basically reusable. For lower mission models, the additional costs associated with design of the ballistic recovery propulsion module, and the reduced payload deliverable to orbit as a result of the higher weight of the recoverable structure, push the trade toward the on-orbit disassembly option. Propellant delivery requirements only dictate 2 to 4 ET Tanker flights per year and other uses for the HLLV only bring the total number of missions to 10 or less by the turn of the century. Therefore, disassembly at the Space Station is the assumed recovery technique.

Basically, the propulsion module is the aft section of the existing Orbiter without the current Thermal Protection System (TPS) and with certain design provisions to aid zero-g disassembly of components. Additional Vernier RCS engines, both forward and aft, aid in Station docking maneuvers. FRSI, LRSI and HRSI insulation is replaced with spray-on foam insulation (SOFI) (similar to that used on the ET) for the side areas while a spray-on ablative foam is used to insulate the aft bulkhead from radiant heat generated by the SSMEs.

A new keel structure attaches to the propulsion module and carries axial loads to the existing ET attach. This minimizes redesign for the ET, which otherwise would have to be stiffened to take the axial loads imparted by the SSMEs. For payload application, this keel structure would carry payload attach frames and a new payload shroud. Payloads up to 90 feet long and 20 feet in diameter could be accommodated.

In operation the ET Tanker follows a direct ascent trajectory to the Space Station at about 220 n.mi. OMS engines or the existing PRCS engines are used for terminal phasing maneuvers. The propulsion module remains attached to the ET until final disassembly and disposition at the Space Station. The ET Tanker docks with the station under manual control from the station using the propulsion module PRCS and VRCS engines.

Once docked, the Propellant Transfer Arms (see Figure 3-43) are swung down and engaged with the existing Shuttle overboard dumps. Propellant transfer is aided by performing Space Station orbit-maintenance burns concurrently. Acceleration levels of 0.0005-0.00010 g required for quarterly orbit-maintenance burns aid in propellant acquisition and transfer to station tanks. Propellant transfer is performed through the existing O_2 and H_2 feed systems on the ET and requires between 5 and 20 minutes. The ET and propellant lines are then vented for several hours.

After propellant transfer and venting the disassembly operation commences. Space Station RMSs, augmented with versatile service attachments, assist EVA crewmen in operations. Key components which could be disassembled and packaged for Shuttle return include:

a. SSMEs

b. OMS/RCS Aft Pods

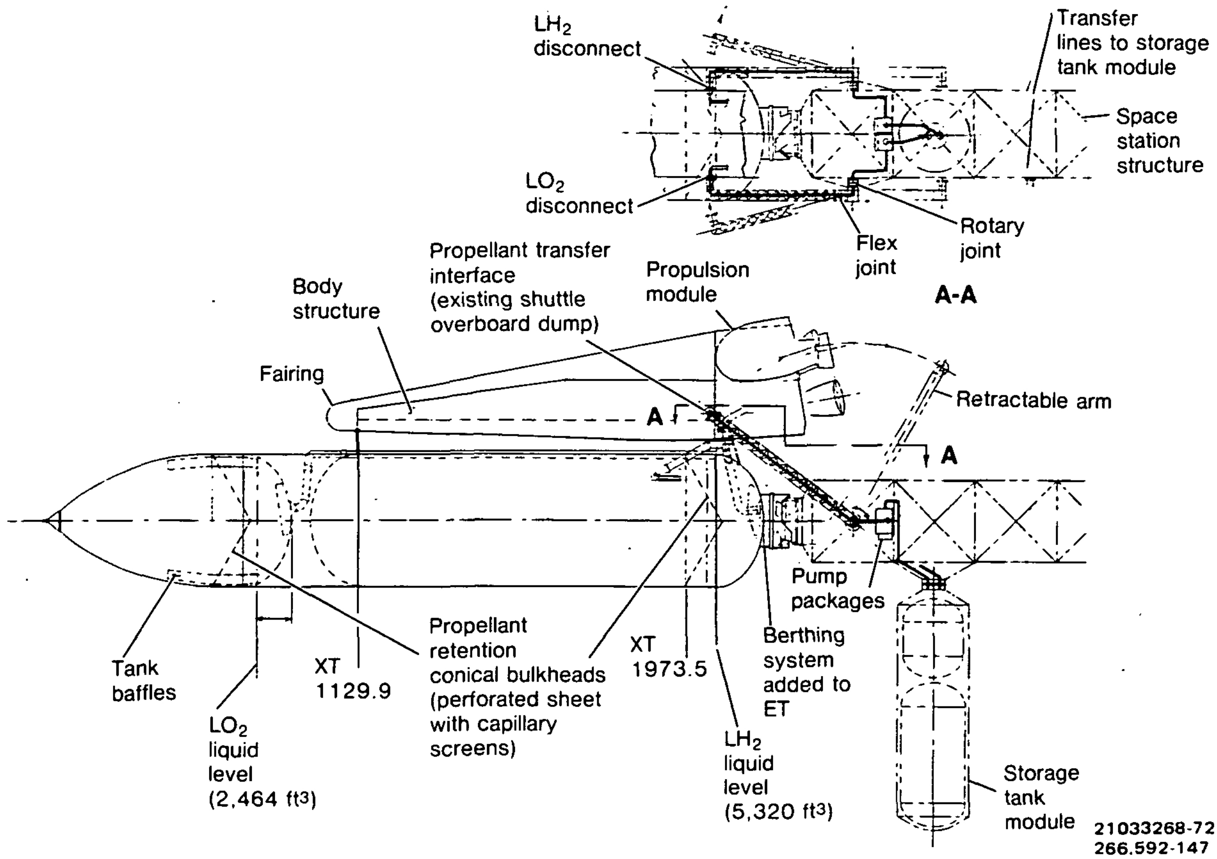

Figure 3-43. ET Tanker Propellant Transfer Concept

c. RCS Forward Pod

d. Engine Controllers

e. Main Avionics Suite

f. APUs

g. Miscellaneous Propellant Pumps, Valve Assemblies, etc.

Preliminary packaging indicates that these components could be returned on two or three Orbiter flights. The ET and remaining structure/hardware could be deorbited by the TMS or placed in a higher storage orbit for later use. ETs could be attached together with the Space Station and Orbiter attachments to reduce drag losses in long term storage.

3.3.3.4 Thermodynamic Analysis of Cryogenic Propellant Delivery Systems - Residual Analysis, Honeybee Scavenging Concept. A preliminary analysis was performed on the ET to assess possible propellant scavenging concepts with an Orbit Transfer Vehicle. The basic scenario that is proposed for propellant scavenging by an OTV is outlined in Section 3.3.3.2.

The propellant residuals available at MECO are given in Table 3-28 for both the LH_2 tank and LO_2 tank, for an 85 percent loaded orbiter at launch and a nominally loaded external tank. Table 3-28 is taken from recently updated JSC data on residuals expected on the external tank at MECO.

Table 3-28. Liquid Residual Available at MECO for Propellant Scavenging, Honeybee Concept

	LO_2 (lbm)	LH_2 (lbm)	LO_2/LH_2 (lbm)
Orbiter	4,629	307	4,936
External Tank	2,001	2,695	4,696
+ 15% Reduced Payload	(10,365)	(0)	(10,365)
Total External Tank	12,366	2,695	15,061

The assumptions that were made in a thermal analysis of the ET to determine the residuals available after MECO are:

a. The propellants remain settled near the aft bulkhead of the ET up to MECO, after MECO before the OTV docking, during the docking and during the propellant transfer operation.

b. The worst case thermal condition prevails during docking, i.e. solar heating of the aft bulkhead of the ET LH_2 tank (25 BTU/sec) and orbiter heating of the LO_2 feedline (15 BTU/sec).

c. The propellants are in a saturated liquid state at 34 psia for LH_2 and 22 psia for LO_2. This is a conservative assumption for liquid residuals for it will give a maximum liquid boiloff for given heating rates.

d. A representative time of 30 minutes for the docking operation of the OTV with the ET. This time will be from MECO to separation of the OTV/ET combination from the orbiter.

Using the above assumptions, it is possible to calculate residuals available after MECO. These are presented in Figure 3-44. The LH_2 and LO_2 liquid residuals are shown against time from MECO. The oxidizer-fuel ratio is also shown so that an understanding can be had of O/F ratios that would be transferred to the OTV. One item to note is the rapid change in the O/F ratio due to the higher boiloff rate of LH_2. The initial low O/F ratio of 4.5:1 is due to the fuel bias (1001 lbm) at liftoff, done to ensure no oxygen rich shutdown of the engines.

The actual transferred liquid quantities are presented in Table 3-29 for four different transfer times. These quantities reflect the residuals remaining in the external tank due to vapor pull-through during transfer.

The actual transfer of liquids from the external tank to the OTV involves several technical issues which must be resolved before a thorough concept assessment is made. Some of these issues are:

1. The Orbiter/ET thermal environment.

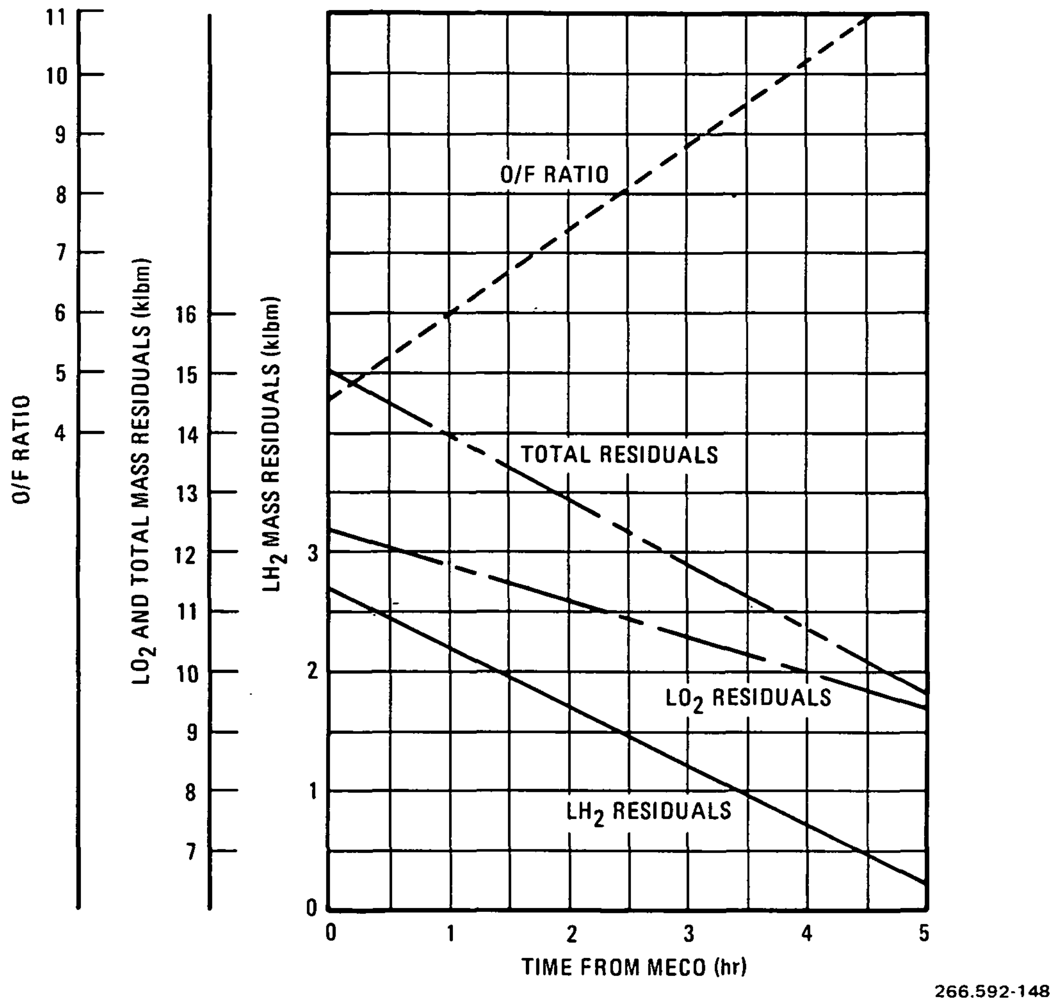

Figure 3-44. Residual Masses and O/F Ratio, Honeybee Concept

Table 3-29. Actual Transferred Liquid Propellants, Honeybee Concept

TRANSFER TIME (MINUTES)	6	30	45	60
Transfer Rate, (gpm) LH_2	625.7	125.14	83.43	62.57
LO_2	221.64	44.33	29.55	22.16
LH_2 (lbm)	1,895	2,073	2,096	211
LO_2 (lbm)	11,589	11,608	11,611	11,612
O/F Ratio of Transfer Mass	6.1	5.6	5.5	5.5
Total Transfer Mass (lbm)	13,484	13,681	13,707	13,723

2. The routing and connection methods of the transfer lines.

3. The pressurization fluid and quantity needed to achieve transfer.

4. Fluid pumping configuration sizing (i.e. type and power needed for transfer pump).

Basically the transfer system needs a better definition so that a meaningful trade study can be performed to assess the Honeybee propellant scavenging concept and what is required (pressurization fluid, electrical power, external tank modifications, and OTV modifications) to acquire the approximately 5,000 gallons of propellants from the external tank at MECO. The concept of propellant scavenging from the external tank appears to be technically feasible from this analysis.

Residual Analysis-ET Dedicated Tanker Concept - The use of the ET as a dedicated tanker has received a preliminary analysis to determine the residuals available for the holding dewars of a Space Station. The assumptions made in the Honeybee concept for the thermal environment and the propellant initial conditions are again used for the dedicated tanker concept to give a "worst case" approach to propellant quantities.

The initial liquid residuals available for propellant transfer are derived for the case of direct ascent of the ET to the Space Station with OMS and/or PRCS firings for orbit phasing. The propellant residuals expected are given in Table 3-30.

Using the assumption of the Honeybee concept for the thermal environment, an estimate of the propellant residuals after MECO can be seen in Figure 3-45. Note that the effect of fuel bias at launch is minimal for such large propellant quantities at MECO so the O/F ratio degrades from a 6:1 ratio.

The liquid quantities transferred to the Space Station dewars assume:

- Propellant transfer starts 4 hours after MECO.

- The Space Station transfer lines are at space temperature of approximately 77K.

Table 3-30. Dedicated ET Tanker Concept, Initial Propellant Masses at Transfer Vehicle MECO

Total Residual Propellants (lbm)	210,000
O/F Ratio	6:1
Initial LH_2 Mass (lbm)	28,571
Initial LO_2 Mass (lbm)	171,429

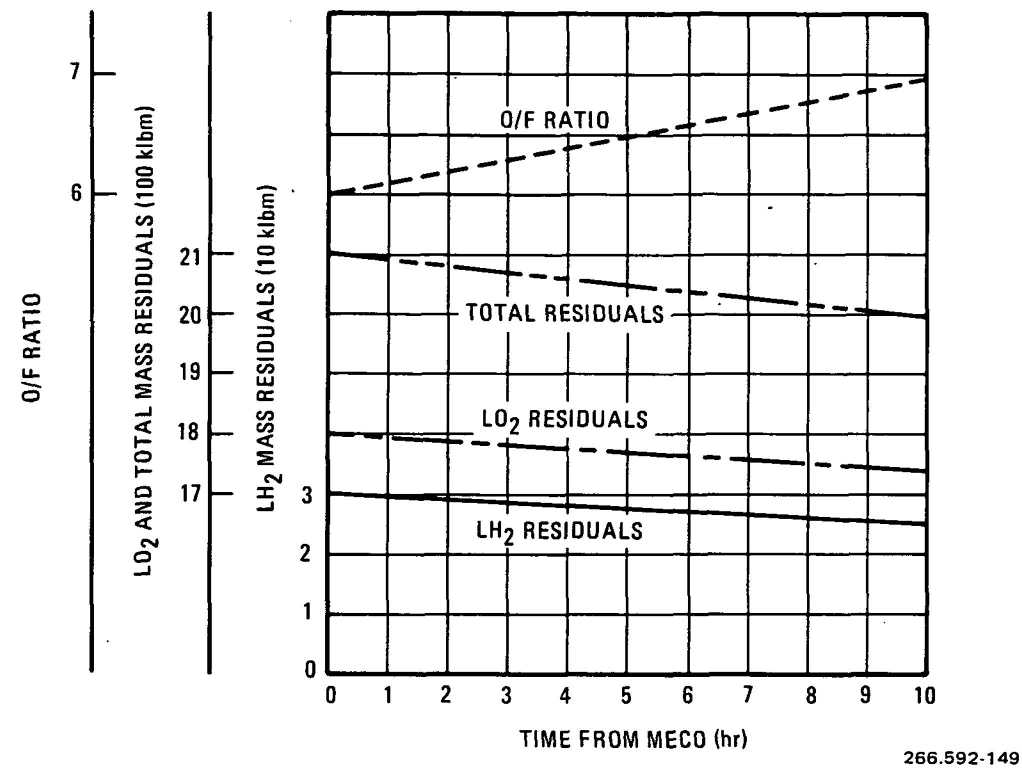

Figure 3-45. Residual Masses and O/F Ratio-Dedicated ET Tanker Concept

- The propellant is retained between the propellant retention bulkheads and aft bulkheads of both LH_2 and LO_2 tanks.

- The transfer vehicle/ET/Space Station is given an acceleration of .0007 g for 4.2 minutes to settle the propellants before liquid transfer occurs.

Using these assumptions, the liquid quantities that can be transferred from the external tank have been calculated and are given in Table 3-31. These quantities are representative of amounts of liquid propellants available, less the vapor pull-through volumes in the tanks and feedlines.

One modification to the transfer technique that would give lower transfer times and low ET residuals would be the use of a variable speed transfer pump, so that as the quantities of liquid approach the pull-through heights, the pumping speed is lowered to a lesser quantity to reduce residual masses.

Some of the technical issues that face the assessment of the dedicated ET tanker concept are:

- The thermal environment of the transfer vehicle/ET combination during operation.

- Complete system sizing of the transfer lines, pressurization lines and power level requirements of the Space Station transfer schematic.

›le 3-31. Actual Transferred Liquid Propellants, Dedicated ET Tanker Concept

:R TIME (MINUTES)	6	30	45	60
Rate, (gpm) LH_2	6,633	1,327	884	663
LO_2	3,073	615	410	307
›	18,734	25,162	25,834	26,159
›	176,753	177,097	177,144	177,171
› of Transfer	9.43	7.04	6.86	6.77
ınsfer Mass (lbm)	195,487	202,259	202,978	203,330

.gn of Space Station tanking dewars.

fications necessary to ET for tanker concept.

hese technical issues facilitates a better understanding of the ·n tanking concept and optimization of the transfer technique and ·n of the most economical method for propellant delivery can thus

Mission Model Requirements. Figure 3-46 depicts propellant per year assuming the entire OTV mission model described in .1.4. These figures therefore represent a maximum propellant Given a nominal 60-80 percent payload capture ratio* the equirements will be reduced correspondingly.

ne on the chart represents actual OTV requirements assuming a 1994 o-year phase-in period before all traffic demand is met. The to the left is only for reference, indicating the entire trend of nt requirements through the decade.

traffic model calling for 40 STS missions total from both KSC and ns likely from an extrapolation of the current mission manifest + missions per year would be accessible from the 28.5-degree Space Ioneybee scavenging. This yields a net propellant delivery of 30k lb per year. This is less than the first year requirements ıp mission model.

:r of the missions going to Ariane, Atlas Centaur II, etc.

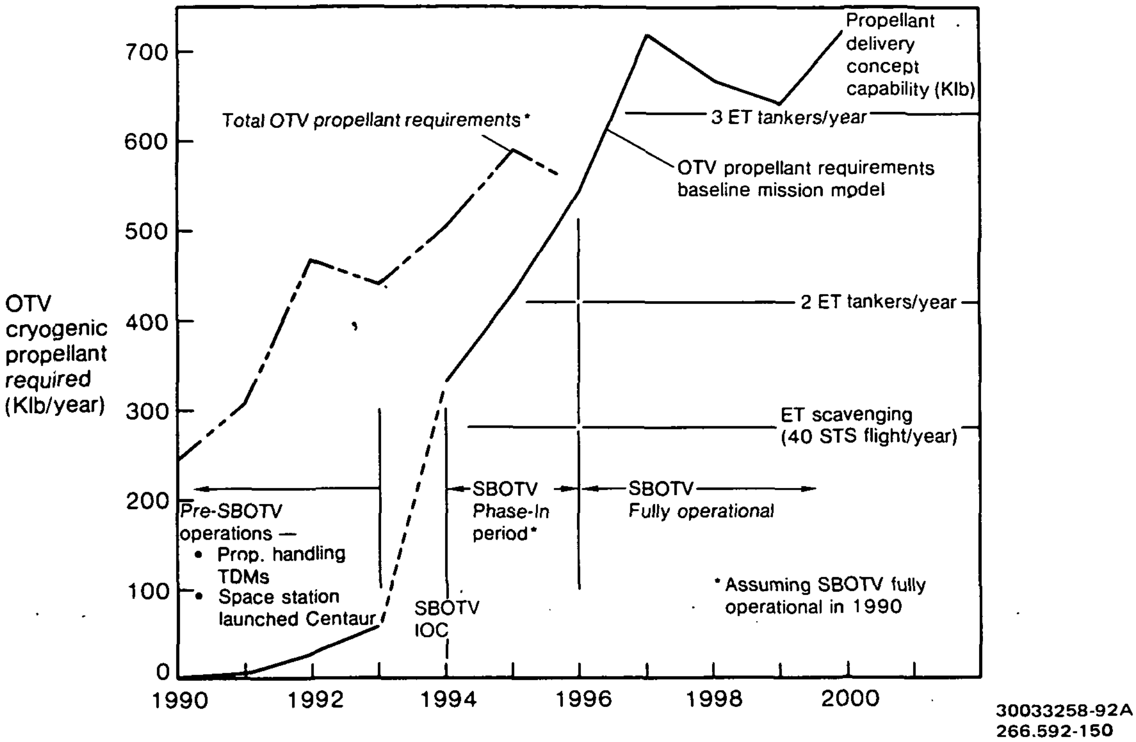

Figure 3-46. OTV Propellant Requirements 28.5-Degree Operations

Therefore, a supplementary means of delivering OTV propellants would be required sometime within the first two years of operation. Carriage of propellant in dedicated payload bay tankage to the Space Station is a logical possibility. However, by 1997 this would require an additional seven shuttle missions just for propellant delivery.

The ET Tanker offers a more plausible means of propellant delivery which is capable of meeting the entire requirement without the added complexity of scavenging concepts and with minimal impact on the STS launch schedule. Only two to three tankers a year will meet the entire requirement and not impose a great burden on the KSC launch facilities.

Hydrazine will be required for satellite ACS replenishment and has been baselined for use by the space station ACS and the TMS due to its low contamination and relative handling simplicity compared with other storable compounds. However, a duel propellant TMS offers higher Isp and scavenging of the Orbiter OMS and RCS tankage is the most economical procedure for supply MMH and N_2O_4 to the Space Station for its operations. Additional safety and reliability concerns with separate propellant tanks in the orbiter are eliminated. Storable propellants carried on the orbiter are summarized in Table 3-32.

Table 3-32. STS Orbiter Storable Propellant

	MMH (lb)	N_2O_4 (lb)	Total (lb)
OMS - Each Pod	(4,505)	(7,433)	--
Total	9,010	14,866	23,876
RCS - Each Pod	(930)	(1,488)	--
Total	2,790	4,464	7,254
TOTAL	11,800	19,330	31,130

For a standard Space Station logistics mission lasting 48 hours, Shuttle Orbiter OMS/RCS propellant requirements are about 30 percent of the totals shown in the table. Allowing for a sizable Flight Performance Reserve on reentry, it can be assumed that 50 percent of the totals would be available for scavenging at the Space Station. Figure 3-47 shows orbiter delivery capability in this scavenging mode along with the right rand axis.

Figure 3-47 shows propellant requirements for a monopropellant TMS by year. Assumed propellant usage for each flight is 70 percent (of the 5,000 lb total capacity), a conservative estimate for this application which illustrates the probable upper limit for TMS propellant usage. Nominal propellant usage for the given mission set is 15-30 percent lower, the use of a conservative propellant usage factor drives out delivery requirements.

A dual propellant TMS using N_2O_4/MMH would require about 25-35 percent less propellant by weight, depending on the exact engine chosen for the vehicle. A dual propellant TMS could be supplied with 10 orbiter scavenging operations per year on the average. This is well within the average number of flights (about 18) required for station logistics and payload delivery for the OTV.

A monopropellant TMS using Hydrazine offers several advantages such as low contamination and simplicity of propellant handling, which resulted in its selection for this study. Hydrazine will have to be delivered to the space station in dedicated Orbiter tankage. Between 5 and 10 shuttle missions per year, (depending on the amount delivered per mission) must comanifest a hydrazine tank module to support monopropellant TMS operations.

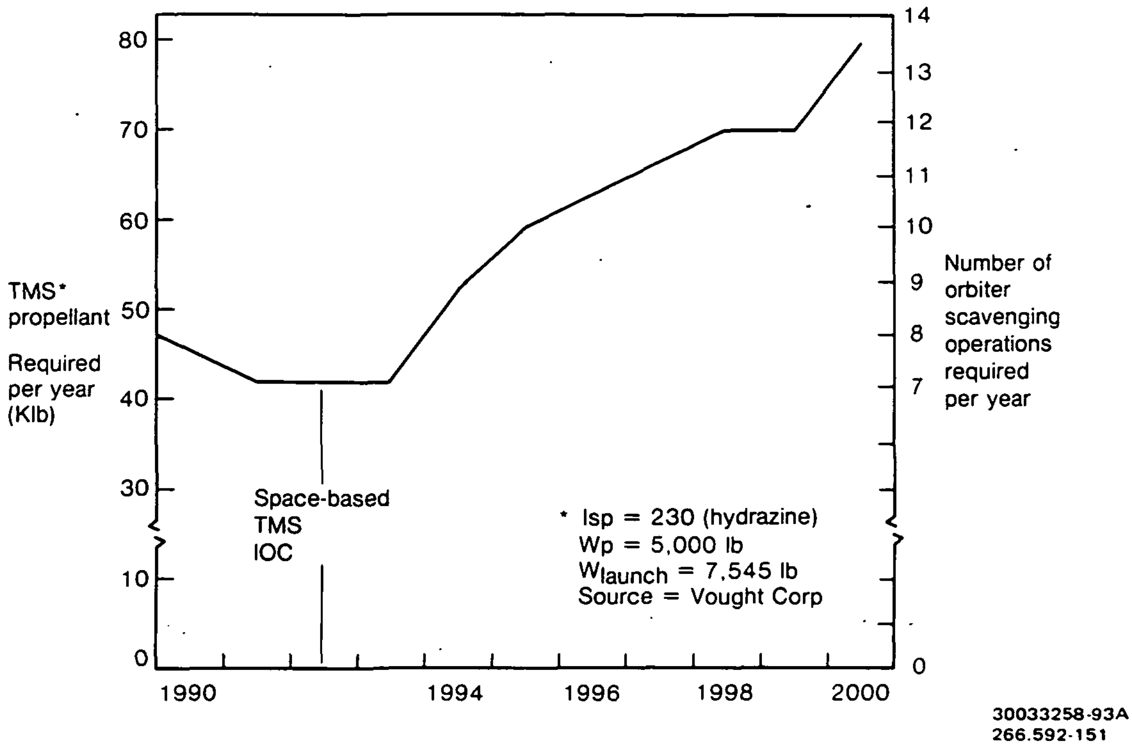

Figure 3-47. TMS Propellant Requirements Per Year 28.5-Degree Operations

SECTION 4

RECOMMENDED SPACE STATION ARCHITECTURE & EVOLUTION

The Space Station System Architectural options and trades evaluation in subsection 3.1 resulted in the selection of a baseline system architecture with one permanently manned Space Station at 28.5-degree inclination. This Section defines the architectural and evolutionary concept for that station, describes its performance benefits and identifies systems technology needs.

4.2 SPACE STATION FACILITIES ARCHITECTURE AND EVOLUTION

The Space Station Architecture and Evolution must satisfy the system requirements developed in Subsection 2.1, system operational requirements of Subsection 2.2 and the subsystems architectural requirements defined in Subsection 3.2. One approach to describing an architecture for the 28.5-degree inclination Space Station is to first define and select major functional elements; second to select a preferred construction approach; and finally to define the orbital facility in terms of the overall composition of elements and their interrelationships.

The evolution of this architecture through the decade of the 1990's is described by showing the progressive addition or removal of functional elements based on the baseline Space Station program and mission set.

4.2.1 ELEMENT CONCEPTS AND TRADES. In order to define the architecture of the Space Station it was necessary to derive those functional elements of the station from the functional analysis of the mission set. The process by which this was achieved was closely related to the definition of the term "architecture." For the purpose of this study, the following loose definition was used: Architecture is a general technical description of a system and its basic elements required to perform the functions that satisfy the operational requirements of a given set of missions. It includes the functional arrangement and interrelationships of the basic system elements without specifying either hardware or geometrical configurations. Thirteen major functional elements were defined during innumerable technical group discussions as being characteristic of a Space Station on an architectural level (Figure 4-1). These functional elements may be divided into three types as follows:

a. Crew Support includes those elements required for the survival of man in space: Habitats (somewhere to live), Logistics (consumables), Safe Havens (emergency life support), and Airlocks (access/egress).

b. Station Support includes the functions required for the maintenance of a spacecraft in orbit: Command (guidance, control, navigation, etc.), Solar Arrays (power supply), Thermal Radiator (thermal control), Remote Manipulation Systems (Shuttle interface, contruction, repair) and General Purpose (miscellaneous required pressurized capabilities).

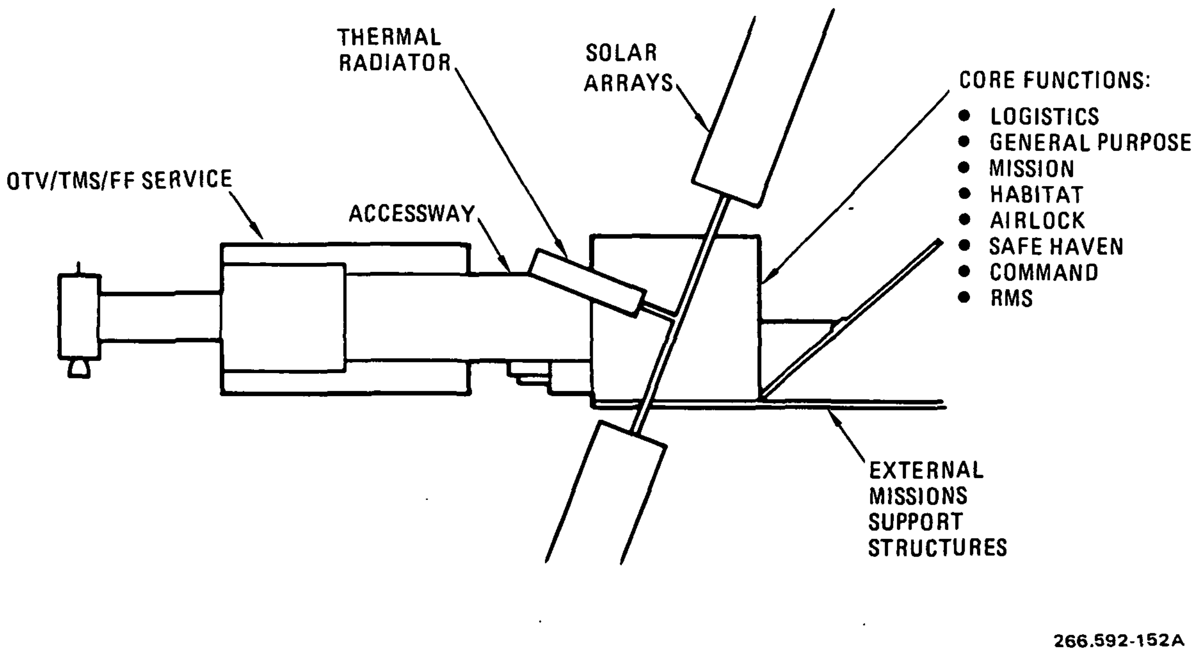

Figure 4-1. Example of Functional Element Architecture

c. Mission Support includes the functions required to operate, maintain, and repair those missions to be performed on the station: Mission Modules (pressurized containers for the mission), External Missions Support Structures (to accommodate the external equipment requirements), OTV/TMS/ Free Flyer Servicing areas (to maintain and repair these units), and Maintenance Modules (to provide shirtsleeve access to portions of the OTV).

4.2.1.1 Elements and Concepts. Alternative concepts were established for each of the functional elements (Table 4-1.). These concept sets are not exhaustive, but are intended to convey potential approaches that could be used for the architectural elements. It should also be noted that the various concepts for individual elements are not necessarily mutually exclusive, but can be used in combination. For example, Mission Modules could exist in combinations of floor orientation directions (Figure 4-2) directions as well as different stacking geometries. These 70 element concepts formed the basis for the functional element trades.

4.2.1.2 Drivers and Concepts. During the process which identified the Architectural Elements, a number of potential driver categories were isolated. At various times during the study, concepts for these drivers were proposed. The Driver Concepts are listed in Table 4-2. The concepts include methods, generic hardware types, and philosophical approaches to solving problems associated with space station architecture. Like the Element Concepts table, the concepts are not necessarily exclusive. The Preferred Driver Concepts (Table 4-3) are discussed in detail below:

Table 4-1. Alternative Functional Element Concepts

ELEMENT	ELEMENT CONCEPT								
SOLAR ARRAY	ONE BOOM	2 BOOMS	MULTILOCATIONS	SUN ORIENTED	TETHERED	μ-WAVE BEAMING			
HABITAT	4 MEN WITH 6 BY 5 FT ROOMS	X MEN WITH 3 BY 3 FT ROOMS	NO WORK IN HAB						
MISSIONS	RADIAL VERTICAL	LONG AXIS VERTICAL	STACK END ON	STACK SIDE TO SIDE	STACK AT RIGHT ANGLES	STACK PARALLEL ON A "RACK" TUBE	STACK RADIALLY ON A "RACK"		
AIRLOCK	ONE PERM. FOR CARGO, ONE FOR MEN	PORTABLE	ONE IN EVERY MODULE	STRATEGICALLY LOCATED	EACH MODULE IS AN AIRLOCK				
SAFE HAVEN	PART OF ANOTHER MODULE	SEPARATE MODULE	SOLAR POWER	BATTERY POWER	CONSUM. STORAGE	DISTRIBUTED HAVENS	MODIFIED ET		
LOGISTICS	SERVES AS PANTRY	SERVES ONLY AS A SHIPPING CONTAINER	DISTRIBUTED LOCATIONS						
ACCESSWAY	INTERIOR TO MODULES	EXTERIOR TO MODULES	MAXIMUM DIAMETER	MINIMUM DIAMETER	OPEN TO WORK AREAS	CLOSED TO WORK AREAS	INTEGRAL WITH MODULES	SEPARATED FROM MODULES	
COMMAND	PART OF HABITAT	PART OF POWER MODULE	PART OF A MISSION MODULE	COMPLETELY SEPARATE	AFFORD MAXIMUM VIEW	COMPROMISED VIEW			
SERVICE MODULE	CONTAINS GIMBALS	HAS PANELS ON IT	NO PANELS	HOLDS ENERGY STORAGE	IS SEPARATE	IS INTEGRAL W/A MISSION MOD	IS INTEGRAL W/SAFE HAVEN		
EXTERNAL STRUCTURE	PLATFORM OFF STATION	RACKS ON STATION	MOUNTED ON SHELL	MOUNTED ON BOOMS					
RADIATOR	SINGLE LARGE UNIT	DISTRIBUTED UNITS	BLACK FIN	LIQUID DROPLET	HEAT PIPE				
RMS	CONVEYOR BELT	DISTRIBUTED ROBOTICS	ONE RMS	TWO RMS	USE SHUTTLEs RMS	MOBILE RMS			
OTV/TMS/FF SERVICE	SEPARATE STATION	COMBINED WITH RD&P	GEOMETRICALLY SEPARATED FROM RD&P						

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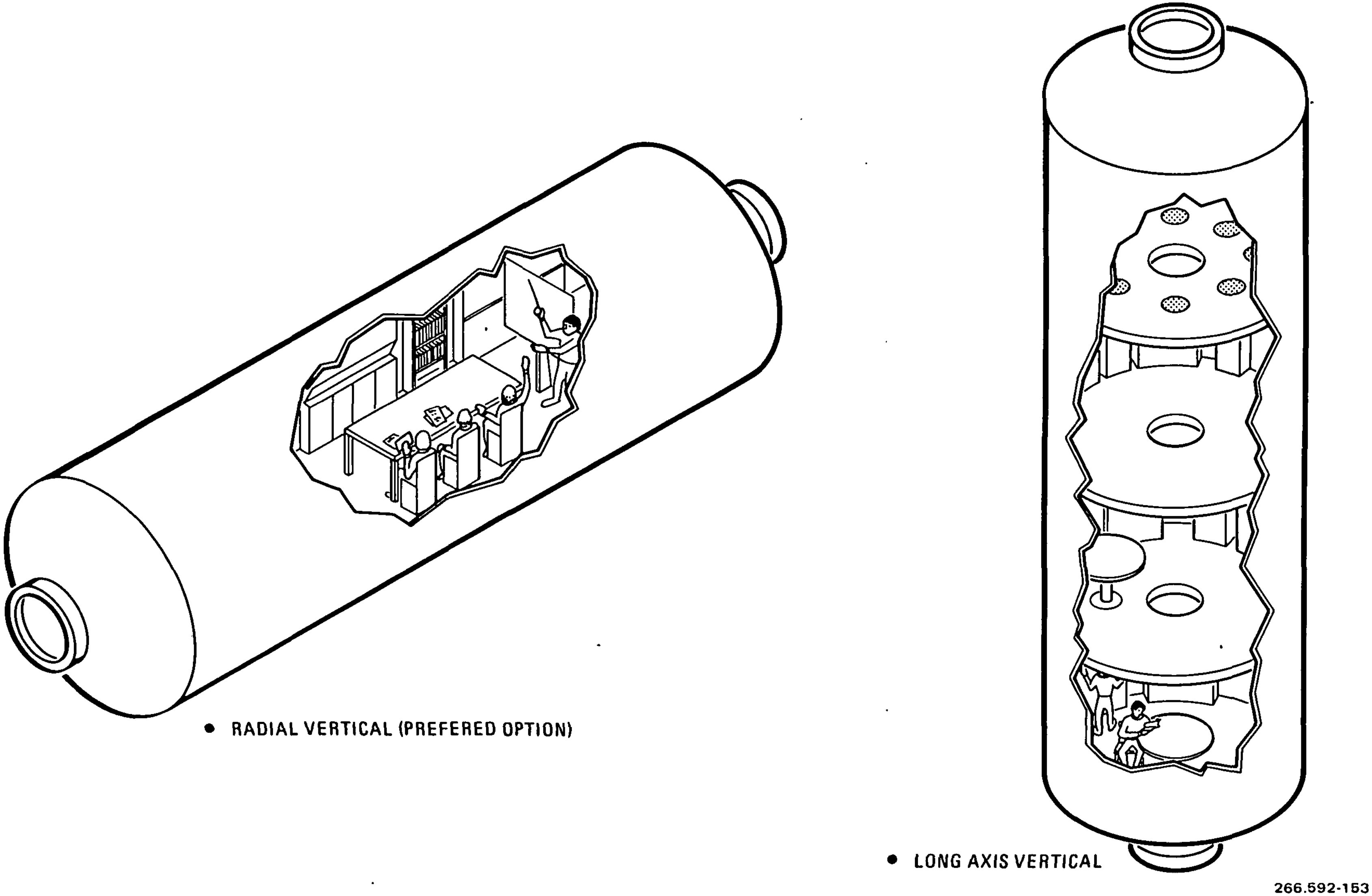

Figure 4-2. Orientation: Radial Vertical Versus Long-Axis Vertical

Table 4-2. Driver Concepts

DRIVERS	SYSTEM DRIVER CONCEPT								
CONSTRUCTION SEQUENCE	MAJOR ON-SITE CONSTRUCTION	PIECEMEAL MODULAR ASSEMBLY							
CONSTRUCTION METHOD	ASSEMBLE FROM & WITH SHUTTLE	ASSEMBLE WITH S/S FACILITIES	TRANSPORT PARTS BY SHUTTLE	TRANSPORT PARTS BY OTV/TMS	BUILD AT LOW ALT & THEN TRANSPORT TO HIGH				
STATION ORIENTATION	SOLAR POINTING	EARTH POINTING	SEMISOLAR POINTING						
FIELDS OF VIEW	TDRSS/TDAS CONSTANTLY IN VIEW OF ANTENNAE	EARTH ENTIRELY IN VIEW OF MISSIONS							
ENVIRONMENT	SUPER CLEAN	AVOID ROCKET EXHAUST	AVOID OVER-BOARD RESIDUALS	PROTECT FROM MICRO-METEOROIDS & DEBRIS	PROTECT FROM RADIATION & SOLAR EFFECTS	ISOLATE MISSIONS FROM DISTURBANCES	ELECTRO-MAGNETIC PROTECTION	OUTGASSING & LEAKAGE	
STS APPROACH AVENUE	SINGLE APPROACH	MULTIPLE APPROACHES	APPROACH CHANGES AS STATION EVOLVES	APPROACH DOES NOT CHANGE					
MODULE CHANGEOUT	MODULES INSTALLED PERMANENTLY	MODULES AVAILABLE FOR CHANGEOUT & RETURN							
FINAL PRODUCT ACCESSABILITY FOR SHIPPING	PRODUCTION MODULES NEAR AN AIRLOCK NEAR SHUTTLE PORT	PRODUCTS MOVED THRU PASSAGES TO THE SHUTTLE PORT	PRODUCTS DEPOSITED DIRECTLY INTO LOGISTICS MODULES & MOVED TO SHUTTLE BY RMS						
SAFETY	CONTROL RE-ENTRY	RESCUE CAPABILITY PERMANENTLY ON-SITE	INCLUDE A SELF DESTRUCT MECHANISM	INCLUDE A BOOST-TO-VERY-HIGH-ORBIT CAPABILITY	RESCUE-AS-AVAILABLE BY SHUTTLE	STANDBY RESCUE VEHICLE ON GROUND	SAFE HAVEN AVAILABLE	STANDBY POWER	
ENERGY STORAGE	BATTERIES INSIDE	BATTERIES OUTSIDE	LARGE GROUP(S) OF BATTERIES	DISTRIBUTED GROUPS OF BATTERIES	FUEL CELLS IN LIEU OF BATTERIES				
LIFE-CYCLE COST	SUBSYSTEM MODULARITY	MINIMAL GROUND SUPPORT	ON-SITE TRAINING	ABILITY TO ACCOM. NEW TECHNOLOGY	AUTOMATION	AUTONOMY	MIN. CREW SIZE	RELIABILITY & MAINTAINABILITY	SAFETY

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Table 4-3. Preferred Driver Concepts

DRIVERS	PREFERRED SYSTEM DRIVER CONCEPT(S)	COMMENTS
CONSTRUCTION SEQUENCE	• PIECEMEAL MODULAR	EASE OF ON-ORBIT CONSTRUCTION OPERATIONS BUT CONSTRAINS PACKAGING OF MISSIONS INSIDE MODULE
CONSTRUCTION METHOD	• ASSEMBLE FROM SHUTTLE WITH RMS & HOLDING FIXTURE • USE AFT CARGO CARRIER FOR LARGE ITEMS	REQUIRES LEAST SPECIALIZATION OF STATION FACILITIES, BUT REDUCES INDEPENDENT CAPABILITY
STATION ORIENTATION	• EARTH ORIENTED	FACILITATES DOCKING MANEUVERS, REQUIRES SECOND GIMBAL ON SOLAR ARRAYS
FIELDS OF VIEW	• TDRSS/TDAS IN MAXIMUM VIEW • EARTH MOSTLY IN VIEW OF MISSIONS	REQUIRED FOR OPERATIONS & MISSION PERFORMANCE; RESTRICTS GEOMETRIES
ENVIRONMENT	• AVOID EXHAUST, RESIDUALS • PROTECT FROM RADIATION METEOROIDS & DEBRIS • ISOLATE MISSIONS FROM MODERATED DISTURBANCES	REQUIRED FOR MISSION PERFORMANCE
APPROACH AVENUE	• MULTIPLE APPROACHES • INCREASE NUMBER	MAXIMIZES FLEXIBILITY OF PAYLOAD HANDLING; INCREASES NUMBER OF AREAS OF DIRECT RCS CONTAMINATION
MODULE CHANGE OUT	• CORE MODULES PERMANENT • COMMAND • HABITATS • POWER • SOME MISSIONS • SOME MODULES TEMPORARY (LOGISTICS MISSIONS)	PERMANENT MODULES INCREASE THE NUMBER OF GEOMETRIES AVAILABLE, BUT DECREASE CAPABILITY TO UPGRADE TECHNOLOGY
FINAL PRODUCT ACCESSABILITY FOR SHIPPING	• DIRECT DEPOSIT LOGISTICS MODULES • LOCATE AIRLOCKS NEAR PRODUCTION	RETAIN FLEXIBILITY WHILE PROVIDING VARIETY; REQUIRES MORE SHUTTLE HOLDING POINTS
SAFETY	• CONTROL RE-ENTRY • SAFE HAVEN • FAIL-SAFE DESIGNS • EVENTUAL EMERGENCY MANNED RE-ENTRY UNIT	REQUIRED BY GROUND RULES
ENERGY STORAGE	• FUEL CELLS OR BATTERIES • DISTRIBUTED	EFFICIENCY QUESTION IS STILL OPEN; SAFETY CONCERNS DICTATE DISTRIBUTION
LIFE CYCLE COST	• EMPHASIS ON AUTONOMY, RELIABILITY, AND GROWTH FLEXIBILITY	PROVIDE CAPABILITY TO ACCOMODATE UNANTICIPATED GROWTH, EMPHASIZE CREW ACCOMODATION TO MINIMIZE GROUND SUPPORT, USE FEDERATED DISTRIBUTED SUBSYSTEMS TO PRECLUDE TOTAL SUBSYSTEMS LOSS, ALLOW FOR SUBSYSTEMS UPDATE.

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a. The piecemeal modular construction sequence was chosen on the basis of a more readily available level of technology in the 1990's. Although a Space Station can be used to explore the possibility of constructing large structures and pressure vessels in orbit, it is unreasonable to assume that such techniques would be developed for use on the first generation facility. Selection of this concept drives the architecture to being highly compartmentalized and specialized.

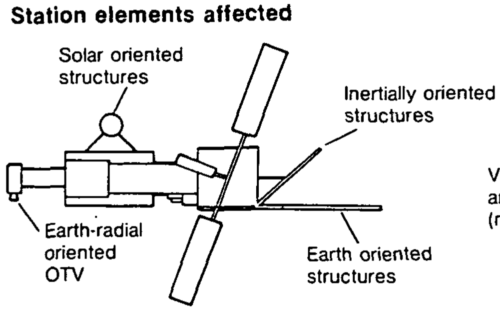
b. The mission set requires the simultaneous maintenance of three station orientations: Earth, solar, and inertial. This will require the use of a set of double gimbals for each external structure affected. Obstructions to fields of view will exist, and variable gimbal rates and tracking patterns will be required to avoid them. An earth-oriented Station appears to be the best recommendation at this time, since more structure is required by the mission set for earth observation missions, and an earth oriented Station would facilitate tracking and docking maneuvers, providing advantages which outweigh the adverse effects of having two gimbals on the solar and inertially oriented structures. It also facilitates propellant transfer operations for the OTV and TMS fueling.

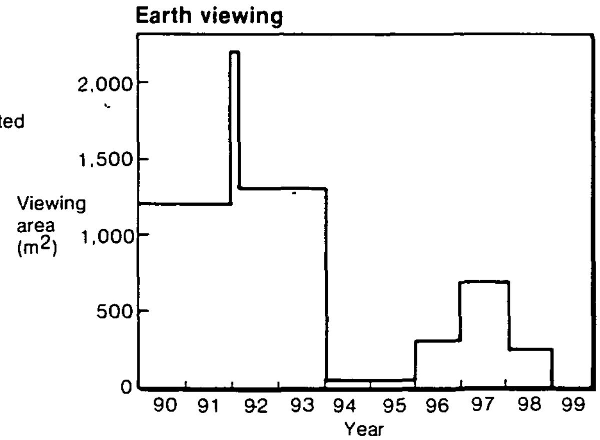
c. Three major fields of view will be required to satisfy the orientation requirements mentioned above. The large external structures required to accommodate the viewing areas summarized in Figure 4-3 will be a major technology driver during the development phase of the station. They will require active control technologies driven by the stringent pointing requirements evidenced in mid-decade. A related problem is that of structural dynamics and spacecraft control, both of which will be affected by the large flexible structures that will be required.

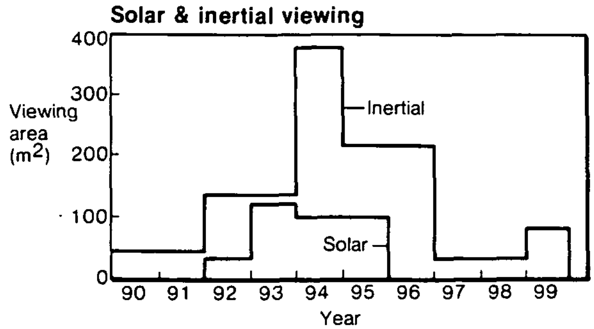
d. The ideal environment for Space Station missions would be clear and free of all contamination and disturbance. However, it is recognized that there will be many unavoidable disturbances to the environment in and around any facility. The missions on the facility will thus have to provide some level of tolerance to them or be otherwise protected from their effects. These disturbances will also drive the general arrangement of station elements to minimize such conflicts.

e. Shuttle OTV and TMS approach avenues should be strategically located to maximize direct access to the various elements. As the Station grows, the number of approach avenues must also grow in order to provide such access. Contamination control devices and techniques will be required to prevent local contamination of missions. Station architecture should incorporate the capability to change geometry as required to allow for these growth problems.

f. Module Changeout will be required. However, core elements should be permanent installations wherever practicable. This will allow many more geometrical arrangements of elements by decreasing the number of modules to which Shuttle access must be provided. Other elements, particularly logistics modules, will be subject to frequent changeout.







Pointing accuracy (arc sec)

Orientation	1990-1993	1994-1996	1997-1999
Earth	360 to 1200	36 to 18,000	360 to 3,600
Solar	10,000	36 to 900	900
Inertial	96 to 360	96 to 360	180

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Figure 4-3. Required Pointing, Viewing & Orientation Summary

g. During the years in which production missions are in existence on the Station, final products must be accessible for shipping purposes. Given that some type of RMS will be avialable on the Station, it appears highly beneficial to deposit commercial products directly into shipping containers which could subsequently be detached and held for shipping. This will also affect the approach avenues and location of the modules containing the production missions.

h. Safety will be a major growth issue that must be planned early in the design to allow for the growing complexity of an evolutionary station. See also Subsection 3.2.6.1.11.

i. The major open question in energy storage is the storage medium itself. No decision has been made between batteries or fuel cells. If a highly distributed energy storage philosophy is used, the architecture will have to reflect this by making provisions for such storage on most, if not all of the modules present on the Station.

j. The Life Cycle Cost of operating and maintaining the Space Station over a period of 10-20 years must be minimized by assuring greater autonomy, reliability and potential for growth. Measures must be taken early in the System design to provide greater autonomy for the flight crews in conducting the operation of the Station. The application of distributed or loosely coupled subsystems will permit incremental system technology updates while preventing total catastrophic shutdown of major critical subsystems. Sufficient scar must also be provided to accommodate unanticipated system growth.

4.2.1.3 Driver and Element Linking. To better understand the relationship between the driver and the functional elements, a linking matrix was prepared as shown in Table 4-4. From this matrix it can be seen that the four most significant drivers are construction sequence, construction method, safety, and life cycle costs, closely followed by module changeout.

It can also be seen that Station Orientation and Final Product Accessibility have relatively little affect on the overall architecture, although they can be expected to heavily influence the eventual configuration of the Space Station.

4.2.1.4 Preferred Element Concepts. Combining the preferred driver concepts and relative importance of drivers, a preferred concept for each of the functional elements was developed. The results are summarized in Table 4-5, and are discussed in somewhat greater detail below:

a. Use of dual booms for the solar arrays increases system reliability and reduces shadowing by distributing the solar arrays. This will, however, decrease the number of approach avenues available. Use of double gimbal sets allows the Station to be earth-oriented.

Table 4-4. Driver Versus Element Relationships

DRIVER \ ELEMENT	SOLAR ARRAYS	HABITAT MODULES	MISSION MODULES	AIRLOCK(S)	SAFE HAVEN(S)	LOGISTICS MODULE(S)	PASSAGEWAY(S)	COMMAND CENTER	SERVICE MODULE(S)	SUPPORT STRUCTURE(S)	RADIATORS	REMOTE HANDLING SYSTEM	SERVICING FACILITIES
CONSTRUCTION SEQUENCE	X	X	X	X	X	X	X	X	X	X	X	X	X
CONSTRUCTION METHOD	X	X	X	X	X	X	X	X	X	X	X	X	X
STATION ORIENTATION	X		X								X		X
FIELDS OF VIEW	X		X					X		X			X
ENVIRONMENT	X	X	X		X					X	X		X
APPROACH AVENUE	X		X	X	X	X		X		X	X	X	X
MODULE CHANGE OUT	X	X	X		X	X	X	X	X	X	X	X	
PRODUCT ACCESSABILITY			X	X		X							
SAFETY	X	X	X	X	X	X	X	X	X	X	X	X	X
ENERGY STORAGE	X	X	X		X				X	X	X	X	
LIFE CYCLE COSTS	X	X	X	X	X	X	X	X	X	X	X	X	X

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Table 4-5. Preferred Element Concepts

ELEMENTS	PREFERRED ELEMENT CONCEPT(S)	COMMENTS
SOLAR ARRAYS	• DUAL BOOMS (DISTRIBUTED) • DUAL GIMBALS	INCREASES RELIABILITY OF INDIVIDUAL GIMBALS, DECREASES SHADOWING, BUT TIGHTENS SHUTTLE APPROACH WINDOW
HABITAT MODULE(S)	• NO WORK DONE IN HABITAT • 3 TO 5 MEN PER MODULE	"NO WORK" PROVIDES PSYCHOLOGICAL ESCAPE FOR CREW
MISSION MODULE(S)	• LONGITUDINAL SLICE • STACKING GEOMETRY OPEN	LONGITUDINAL SLICE EASIER TO ACCESS, PACKAGE, AND SIMULATE STACKING GEOMETRY TRADES ARE VERY COMPLICATED
AIRLOCK(S)	• STRATEGICALLY LOCATED LOCKS • PORTABLE LOCK	LOCKS INCREASE ACCESSABILITY AND FLEXIBILITY PORTABLE AND DISTRIBUTED
SAFE HAVEN(S)	• PART OF SERVICE MODULE • BATTERIES & CONSUMABLES STORED INTERNALLY • SOLAR POWER AVAILABLE • GROWTH: DISTRIBUTED HAVENS W/FUEL CELLS	MAXIMIZES THE INDEPENDENT NATURE OF THE SAFE HAVEN
LOGISTICS MODULE(S)	• SERVES AS "PANTRY" • SHIPS EQUIPMENT, FOOD AND FUEL	MAXIMIZES MODULARITY OF SHIPPING FACILITIES, BUT REQUIRES ANOTHER MAN RATED MODULE DESIGN
PASSAGEWAYS	• DIAMETER SIZED FOR EQUIPMENT MOVEMENT • INTEGRAL & SEPARATE TO MODULES • NONHAZARDOUS UTILITIES LINES	MIXED INTEGRAL AND SEPARATE PASSAGES TO INCREASE FLEXIBILITY OF GEOMETRY
COMMAND CENTER	• PART OF A MISSION MODULE • COMPROMISED VIEWING	DOES NOT REQUIRE ENOUGH VOLUME TO WARRANT A SEPARATE MODULE COMPLETE VIEWING WOULD SEVERELY LIMIT GEOMETRY OPTIONS AND GROWTH
SERVICE MODULE(S)	• IS SEPARATE, CONTAINS SAFE HAVEN • HAS ARRAYS MOUNTED ON IT • DOES NOT CONTROL ALL ENERGY STORAGE	HAVEN LOCATED HERE TO PROVIDE ACCESSIBILITY TO POWER SOURCES ARRAYS MOUNTED HERE BECAUSE IT IS THE FIRST MODULE FLOWN
EXTERNAL SUPPORT STRUCTURE(S)	• RACKS & BOOMS ON STATION EXTERIOR • CONTAIN ENERGY STORAGE, MISSIONS, AND COMMUNICATIONS	MODULARITY IMPROVED BY MOUNTING EXTERNAL EQUIPMENT ON RACKS AND BOOMS INSTEAD OF ON MODULE SHELL
RADIATORS	• SINGLE LARGE INITIAL UNIT • EVENTUAL GROWTH TO DISTRIBUTED UNITS • INITIAL USE OF BLACK FIN TYPE	EVENTUAL DISTRIBUTED UNITS WILL REDUCE GROWTH SYSTEM COMPLEXITY
REMOTE HANDLING SYSTEM	• INITIALLY RELY ON SHUTTLE RMS • GROW TO DISTRIBUTED OR MOBILE SYSTEM	USE SHUTTLE RMS FOR INITIAL CONSTRUCTION TO REDUCE COMPLEXITY OF COMMAND CENTER. ADD STATION RMS LATER TO REDUCE APPROACH AVENUES.
SERVICING FACILITIES	• SAME STATION • OPPOSITE END FROM R&D	SAME STATION REDUCES OVERALL COST OPPOSITE END MINIMIZES ENVIRONMENTAL CONFLICTS

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b. It is preferred that no work be done in the Habitat Modules. This will provide a phychological escape for the crew which will be important for long stay times. It may be necessary to violate this precept by putting some command functions in one or all of the habitats for safety considerations. Three to five men should be located in each habitat for considerations of human interactions. Further discussion on the Habitat may be found in subsection 3.2.6.

c. The Mission Modules will probably have a radial vertical orientation floor plan (Figure 4-2), which is easier to access, package, and simulate on the ground. The actual geometric arrangement of the modules is still an open question. These Modules will be a standard shell with standard subsystems and typical Spacelab rack accommodations.

d. Airlocks should be distributed and portable to increase system safety, operability and flexibility.

e. The Safe Haven is a highly complex element of the Space Station and discussion of it usually enters the realm of configuration. However, one point of major importance which has been identified is that power must be available to the safe haven in sufficient quantity to allow subsistence by the crew for at least two weeks. This drives the safe haven towards being placed in the general purpose module where the solar arrays would be directly accessible. It might also prove desirable to have distributed safe havens, each with independent power systems.

f. The logistics module has been identified as the primary cargo container for the system. To minimize integral storage volume, it should function as a pantry for food and water and should thus be located near the habitat area. To minimize handling, it should also be used to carry equipment and mission supplies.

g. Passageways for the Space Station must be sized for the internal movement of equipment, which will be mostly standard-size racks. It will be necessary to provide for such movement in laboratory areas as well as between modules.

h. The command functions do not appear to require enough volume to warrant the use of a separate module, hence they will be accommodated in part of a Habitat or Mission Module. Auxiliary command will be located in the safe haven.

i. The general purpose module is the primary core element of the Station. It contains the safe haven an auxiliary command, accommodates the solar array and thermal radiator interfaces, and serves as an overflow accommodation sleeping quarters. Overall, this will be the most complex element of the Station.

j. The external support structure will accommodate all of the communications, sensors and missions on the station. They should provide fittings compatible with the standard pallets proposed for use with the Shuttle. These items will be a major technology driver for the station due to the very large sizes involved.

k. A dual redundant two phase fluid thermal bus is recommended. This subject is discussed in detail in Subsection 3.2.2.

l. The Remote Manipulation System should be capable of growth from an initial Shuttle-type RMS to a distributed or mobile combination of units capable of accessing every part of the Station.

m. The OTV/TMS/Free Flyer Servicing facilities are discussed in detail in Subsections 2.2.1 and 2.2.2.

4.2.2 SPACE STATION CONSTRUCTION

4.2.2.1 Concepts. The most elementary philosphy in Space Station construction is to assemble it in orbit directly from the detail parts (primary construction). This would entail shipping parts and subassemblies to orbit in the shuttle. Assembly jigs, fixtures and tools would also be required. Continuous shuttle presence would be required during the first stages of construction in order to support the extensive EVA required of the builders.

At the other end of the construction spectrum is the single launch system, in which all of the primary elements for the station are packaged into a Shuttle-derivative vehicle. Continuous manned presence could commence with the delivery of a logistics module and crew of a succeeding flight. Mission operations could begin with the shipment of equipment on successive flights. Some single-launch scenarios propose the use of an External Tank which would be refurbished on orbit to accommodate habitat and mission functions.

Midway between the two construction philosophies mentioned above is the concept of launching prefabricated modules into orbit and assembling the station by berthing them together. Continuous manned presence could commence with the first or second launch, depending on the nature of the module contents. Missions operation could begin when equipment becomes available on orbit. This timing depends on the order of delivery of modules to orbit.

4.2.2.2 Trades. The major top level trade criteria and comments are summarized in Table 4-6.

It should be noted that primary construction is almost certainly the long term solution to the construction problem, since there would be virtually no volume limited Shuttle flights in the delivery of raw materials. However, it would require a Space Station on location, since the long stay times required for the crew would be well beyond the ability of the Shuttle to accommodate. Also, the technology for constructing airtight enclosures in space is simply not available for this early time frame.

With primary construction being ruled out by the unavailability of the required technology, the trade becomes very close, the only discriminators being in Operations, Safety, and Growth Potential. The first two are not entirely independent of each other because the growth potential for the Piecemeal Modular scheme is dependent on the addition of modules at berthing ports (which may fail) while the single launch scheme results in the reliance on a single pressure vessel (the ET), the failure of which would be catastrophic to large portions of the station capability.

Table 4-6. Construction Trades.

CRITERION	CONSTRUCTION METHOD		
	PRIMARY	PIECEMEAL MODULAR	SINGLE LAUNCH (ET)
OPERATIONAL SAFETY	POTENTIALLY VERY HIGH	MODERATE – HAS MANY TWO-PIECE DOCKING PORTS	MODERATE – FEWER PARTS, BUT HAS FEWER SEPARATE PRESSURE HULLS
TECHNOLOGY AVAILABILITY	POOR DURING THE 1990s	VERY GOOD – STRUCTURE COMMON TO SPACELAB, OTHER TECHNOLOGIES WELL IN HAND	VERY GOOD – STRUCTURE MOSTLY COMMON TO SHUTTLE, OTHER TECHNOLOGIES WELL IN HAND
CONSTRUCTION TIMELINES	VERY EXTENDED – BEYOND SHUTTLE STAY TIME CAPABILITY	MODERATE – WELL WITHIN SHUTTLE CAPABILITY	SHORT – INITIAL LAUNCH IS UNMANNED
GROWTH POTENTIAL	VERY GOOD – SHAPES & SIZES NOT LIMITED BY STS	GOOD – LIMITED BY STS CAPABILITIES, BUT CAN SUPPLY EXACTLY THE VOLUME NEEDED	MODERATE – LIMITED BY STS CAPABILITIES, WILL HAVE LARGE EMPTY VOLUME ON ORBIT
OPERATIONS	EXCELLENT – DESIGNED FOR SPACE CONDITIONS RATHER THAN LAUNCH OR GROUND HANDLING	MODERATE – CONSTRAINED BY STS LAUNCH CAPABILITY, BUT HIGH MODIFICATION AVAILABLE	MODERATE – CONSTRAINED BY STS LAUNCH CAPABILITY, BUT VERY LARGE VOLUME AVAILABLE
COST	HIGH – LONGER ON-ORBIT TIME REQUIRED	MODERATE – MINIMIZES ON-ORBIT CONSTRUCTION TIME	LOW INITIAL – HIGH LIFE CYCLE COST DUE TO SLOW BUILD-UP

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The choice between the two candidates was resolved by a consideration of the amounts of volume being used on orbit. The External Tank schemes would result in very large volumes of pressurized structure being empty for most of the decade. The LH_2 tank generally proposed for conversion to habitable volume contains 1,500 cubic meters, which gives a habitable volume of about $1,030m^3$ at a 70 percent packaging factor. This is the equivalent of eight or nine Space Operations Center (SOC) type modules (Ref. 16). The combined requirement for Habitat and General Mission Modules at the end of the decade is about $960m^3$, which is a reasonable match for the volume available in the LH_2 tank, but the growth pattern of the missions requirements results in the unused volume averaging $500m^3$ over the first six years of operation. The unused volume requires more atmosphere (hence greater leakage) and more environmental control (hence more power and thermal subsystems). On the other hand, it would allow growth for many years without additional primary structure required. Use of the LO_2 tank provides an additional 800 cubic meters - the equivalent of four more SOC-size modules.

The disadvantages of having to install the subsystems on orbit and supply the excess consumables required by the ET concept clearly outweigh the advantage of the extra volume available for growth. Therefore, the piecemeal modular concept is recommended as the preferred concept for Space Station construction.

4.2.2.3 Selected Construction Sequence. The construction of the Space Station from first delivery through Initial Operating Capability (IOC) will require at least five Shuttle flights, described as follows (see Figure 4-4):

1. The initial launch delivers the core of the Station to orbit. This core is in itself a fully functioning spacecraft satisfying all of the basic requirements for manned spaceflight.

2. The second delivery flight emplaces the first accessway and an RMS. These elements are paired due to their relatively small sizes.

3. The third delivery flight emplaces the first Habitat Module on the accessway. A short term crew will power up and checkout the facility at this time, then return on that same Shuttle flight.

4. The fourth delivery flight ships the Portable Airlock, a loaded Logistics Module, and the first of the External Missions Support Structures if there is room available. At this point, the Station can accommodate the first permanent crew.

5. Initial Operating Capability is achieved with the delivery of the first Mission Modules on delivery flight five.

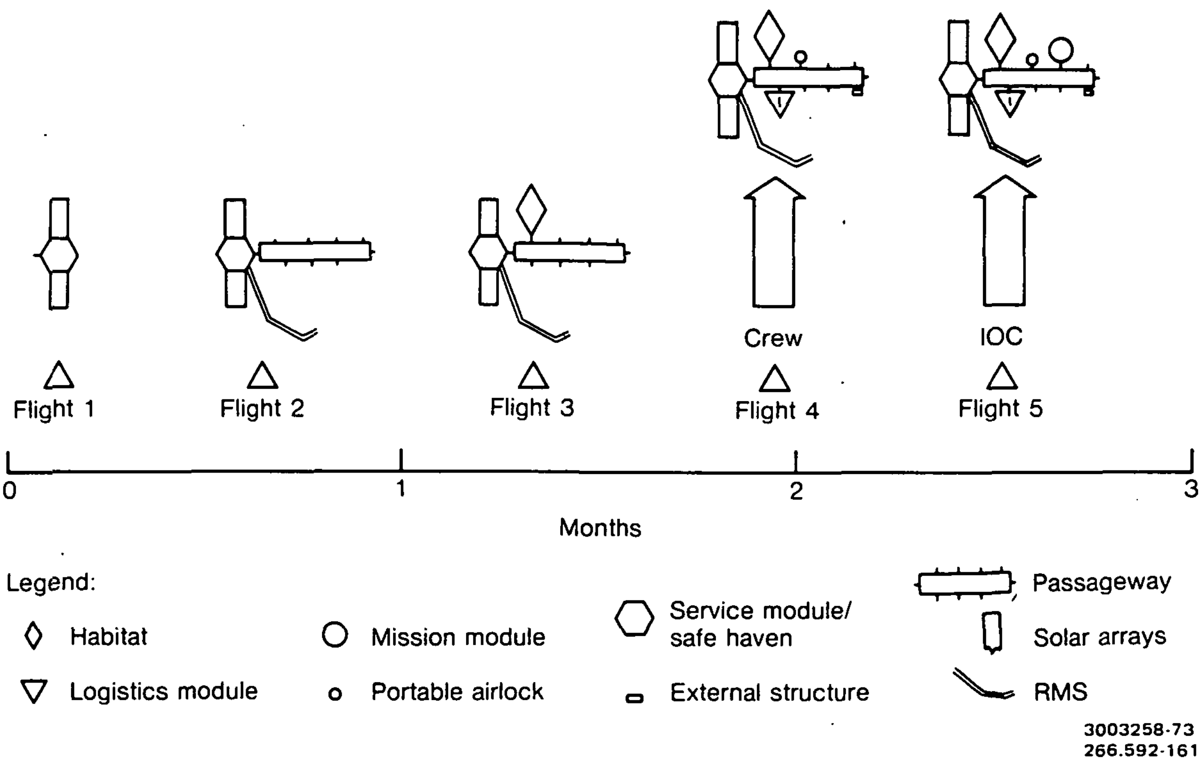

Figure 4-4. Initial 28.5-Degree Space Station Construction Sequence

It should be noted that one extra flight may be required between the first and second flights in order to deliver the primary structure for the Solar Array. If so, the RMS could be delivered then, along with some of the External Support Structures.

Without more detailed configuration data more concise estimates of the construction task are not possible. The subject should be targeted for extensive study, as it affects reconfiguration, maintenance, and many other design factors throughout the Station life time.

4.2.3 SPACE STATION ARCHITECTURE AND EVOLUTION. The fundamental station architecture is primarily driven by the selected construction concept (piecemeal modular). This concept provides the minimum size facility which meets Station requirements at any given time, thus maximizing the opportunity for the development and inclusion of new technology as modules are added onto existing facilities. The best example of this concept is the Closed Ecology Life Support System (CELSS) Module, which is added to the Station in 1996. Assuming a normal development and construction time for this module, three or four years of operational experience with early modules will be available for incorporation into this module. The same philosophy may be applied to the second Habitat Module, and the second Maintenance Module.

The modular arrangement also provides for a highly distributed subsystems capability, increasing safety factors and ease of new technology incorporation into existing units as well as new modules.

The fundamental evolutionary philosophy is to provide very little "extra" volume in the facility at any given time. Unused volume would be a drain on the "owner" of the Station (NASA) without providing any return of scientific or economic value. Of necessity, this increases the number of construction flights and spreads them throughout the decade, but this does not pose a serious problem for the STS.

4.2.3.1. Initial Station Architecture. On an architectural level, the Space Station is composed of five major types of components: Permanent Pressurized Modules, Accessways, Temporary Logistics Modules, External Structures, and Servicing Elements.

Four permanent pressurized modules (Figure 4-5) are required in 1990 to accommodate the initial set of missions. These modules are limited only by the size of the shuttle cargo bay, all being about 14m long by 4.2m diameter. There are two specialized mission modules, one specialized habitat, and one General Purpose Module which combines elements of both of the other types, and serves as a command center and utilities interface.

One Temporary Logistics Module is required in 1990. It serves as a pantry and remains on site for an entire 90 day crew stay time.

Sufficient External Structures are provided to accommodate the externally mounted equipment required for performance of the mission set.

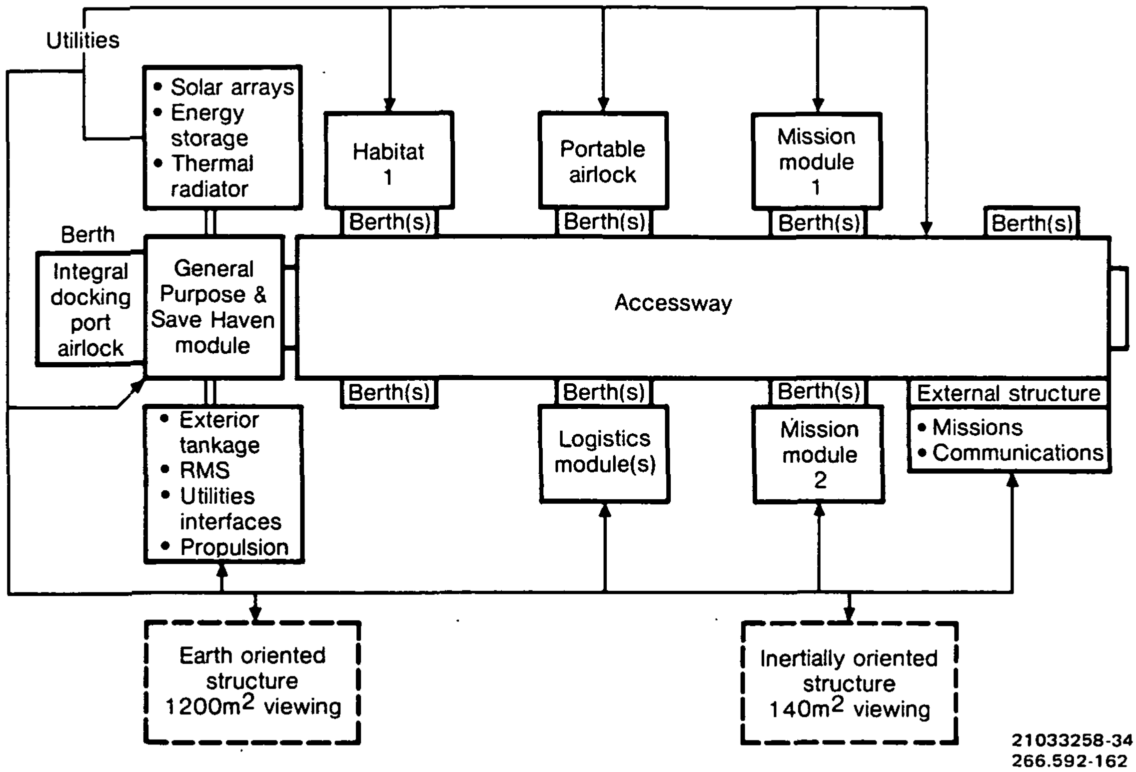

Figure 4-5. Initial Station Architecture

During the initial phase of Space Station operation, no OTV, TMS, or FFS facilities are provided. However, temporary facilities will be provided to accommodate Technology Development Missions (TDM) for these functions, and an initial TMS/FFS operating capability in 1992.

4.2.3.2 Mid-Decade Station Architecture. The first major growth phase occurs in late 1993 and early 1994 with the additional Mission Modules to accommodate the increased mission set, and additional accessway, added to accommodate the new Modules. Mission Module No. 5 is added near the OTV servicing facility to serve as an OTV command center and shuttle docking facility (Figure 4-6).

A second Habitat has been added to accommodate the increased crew size. Crew overflow can be accommodated in the General Purpose Module.

Additional External Structure is provided for Solar Oriented mission equipment.

In late 1993/early 1994, the additional structure required to accommodate the OTV, TMS, and Free Flyer Servicing operations will be attached to the Space Station core. This consists of two trusswork Strongbacks, a Multiple Docking Adaptor, and two Accessways. The TMS and Free Flyer Servicing areas will be provided for the Strongbacks by the platforms, fixtures, and utilities interfaces appropriate for these uses. OTV operations are accommodated by the Hangar and Maintenance Module. Propellant Storage is provided by Modules located near the Hangar, on the Strongback assembly.

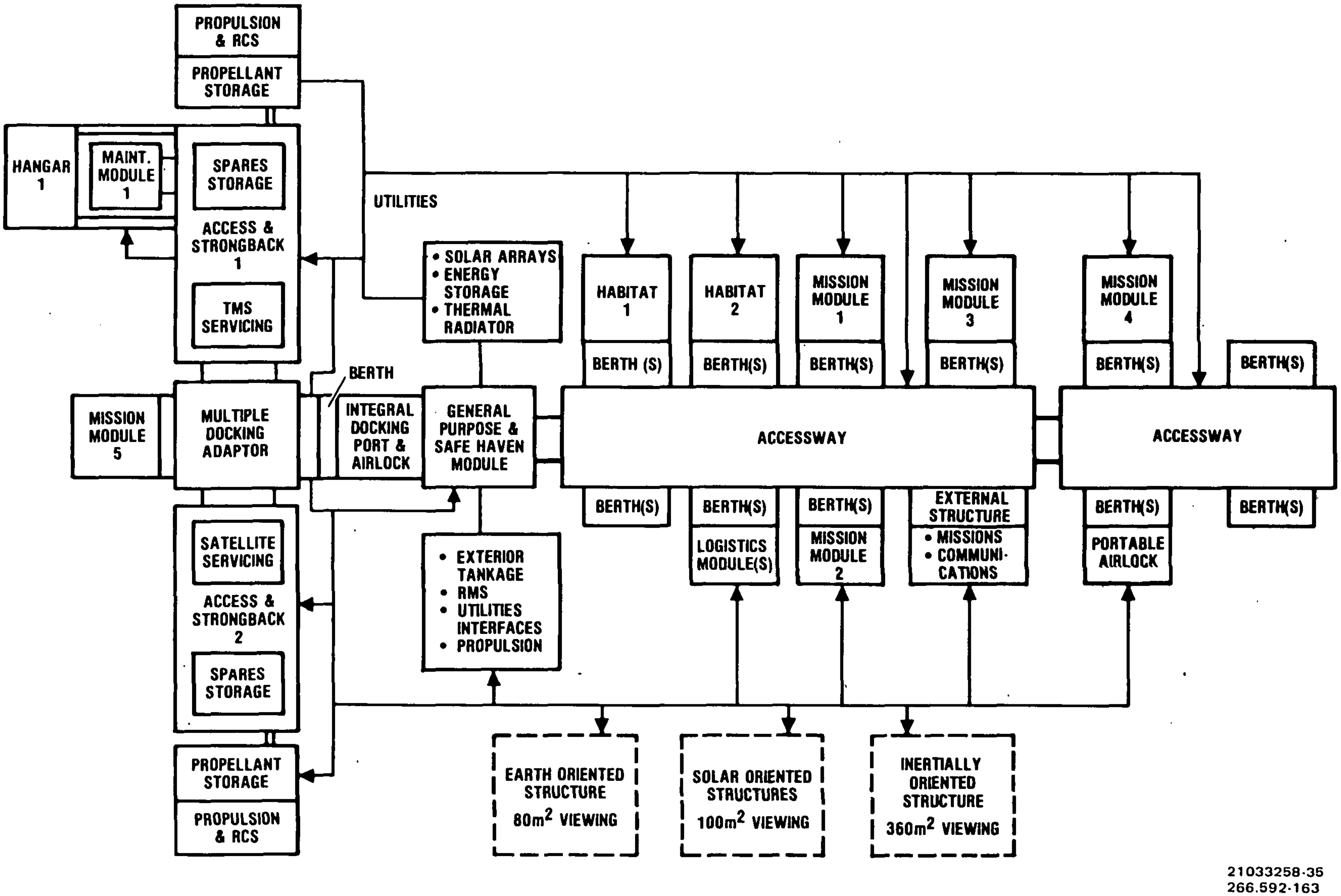

Figure 4-6. Mid-Decade Station Architecture

4.2.3.3 Year 2000 Station Architecture. In 1996 a sixth Mission Module is added, which contains the Closed Environmental Life Support System (CELSS) (Figure 4-7).

Further growth is possible with the addition of more modules to existing accessways, and with the addition of more accessways in parallel to the first two. The strongback structure may be extended to accommodate more Maintenance Modules, Multiple Docking Adaptors, and Mission Modules.

The growth of the Habitable Volume on the Station is shown in Figure 4-8.

In 1996, the second OTV Servicing Facility will be added to the Strongback. At this time, sufficient manpower and facilities will exist for the operation of two OTVs.

4.3 SYSTEM TECHNOLOGY NEEDS

Development of new system technologies will be required to support a full-capacity Space Station. These technologies generally span across the subsystems discussed in subsection 3.2. Hence, system technology needs overlap some aspects of subsystems technology.

4.3.1 LARGE SPACE SYSTEMS TECHNOLOGY

4.3.1.1 Automated Space Construction. It is apparent that several very large external support structures will be required to accommodate the large number of externally mounted missions during the 1990s. Automated construction of these units would potentially save hundreds of man hours of Extra Vehicular Activity (EVA).

4.3.1.2 Extra Vehicular Support Systems. The 8 psi suite and advanced glove are currently in development, and will be required for extensive operations from the Station. Cherry-picker type work stations, improved communications techniques, and rescue systems will also be required.

4.3.1.3 Shuttle Berthing and Docking Operations. The total disturbances introduced to the Station by the Shuttle docking sequence must be definitivly quantified in order to provide guidelines for the design of the systems required to isolate the Research & Development missions from the effects of close proximity Shuttle activity.

4.3.1.4 Module Berthing and Safing. Module berthing with full utilities hook-up will be a precise and difficult operation. Targeting and confirmation systems and self-test safing systems will be required for routine expansion of Space Station facilities.

4.3.2 FAILURE DETECTION SYSTEMS. Automatic built-in test systems will be required for continuous monitoring for all major safety and life support functions. Alarm systems and emergency actuation of automatic airtight doors and seals may also be required. Precatastrophic failure danger symptoms must be detected early to allow on-site preventive maintenance prior to failure.

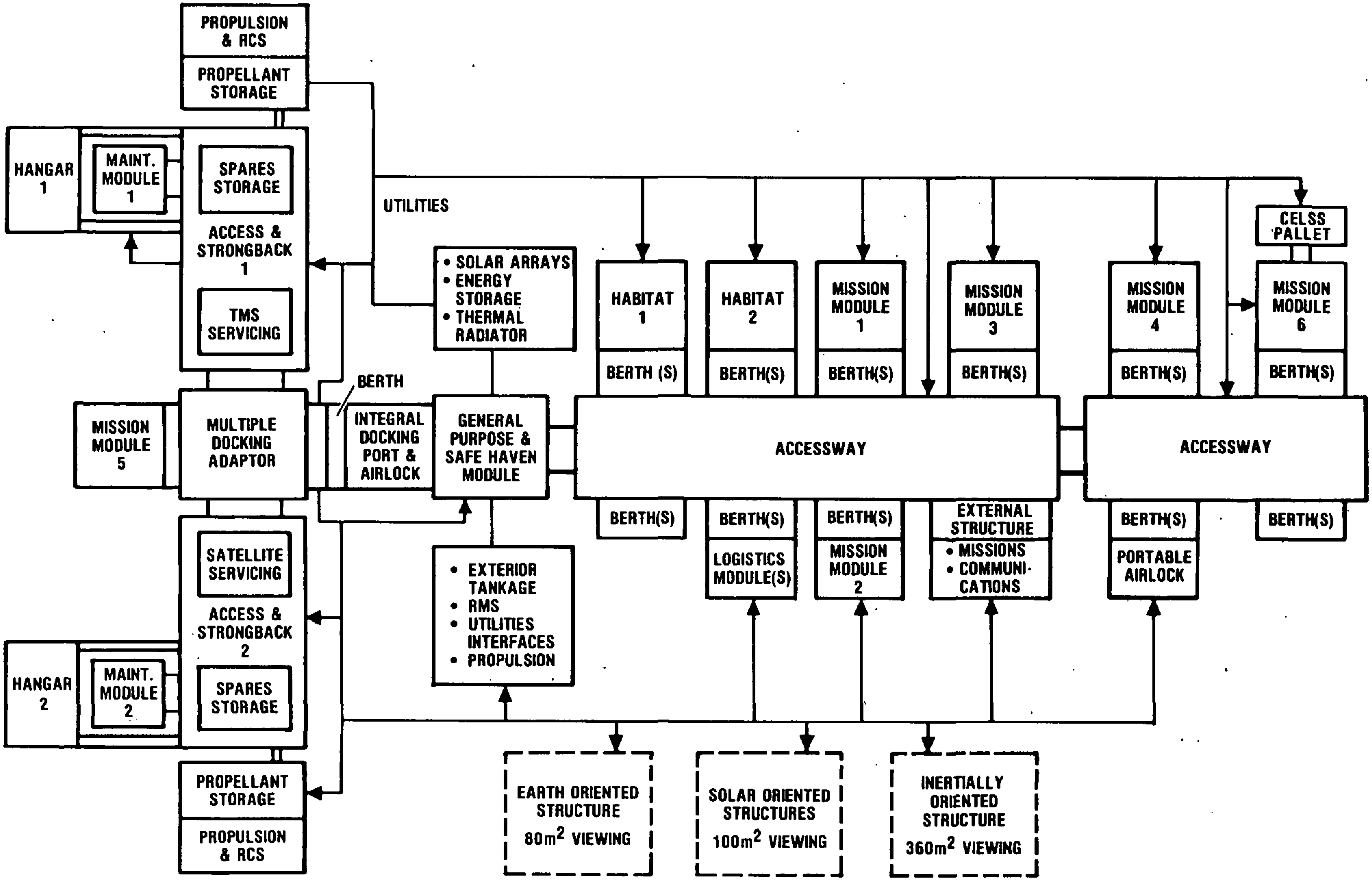

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Figure 4-7. Year 2000 Station Architecture

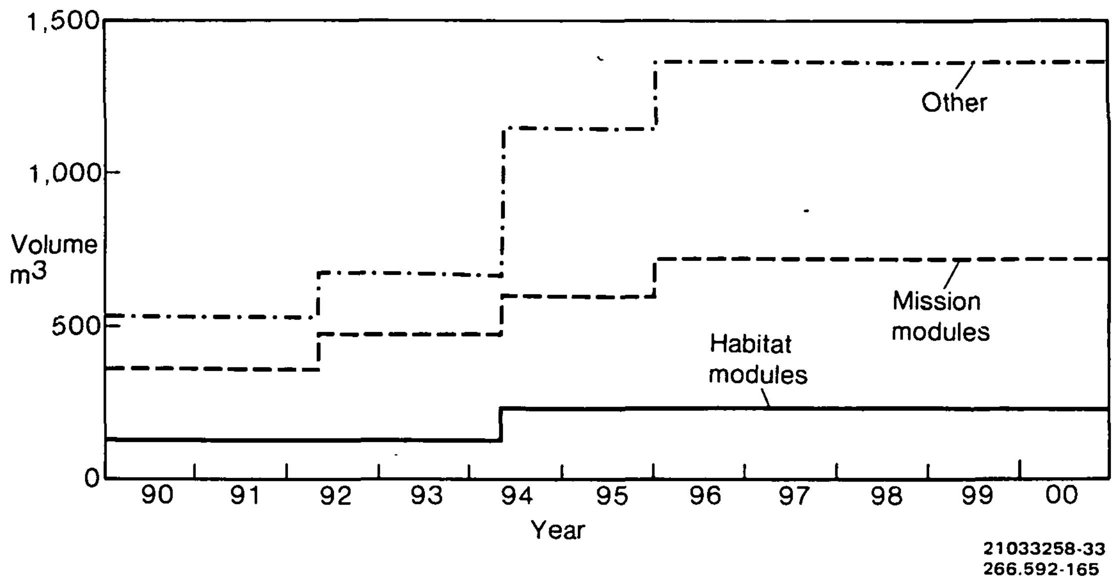

Figure 4-8. Habitable Volume Growth

4.3.3 POWER AND THERMAL CONTROL INTERFACE MODULARITY AND GROWTH. Power and Thermal Control requirements increase by half an order of magnitude during the first decade of operation. The power and thermal busses must be capable of either accommodating the growing requirements, or of being expanded by installing several identical (or upgraded) units in parallel in order to handle the increased demands on the Station.

4.3.4 MISSIONS PROTECTION SYSTEMS AND INTERLOCKS. Missions will exist on the Space Station which will have operational conflicts with other missions. Means must be provided for the protection of payloads, and interlocks must be provided to prevent the accidental simultaneous operation of conflicting missions. This will require a highly integrated data management and software subsystem.

4.3.5 SUBSYSTEM UP-GRADE CAPABILITY. Significant advances in technology may be anticipated during the operational lifetime of the Space Station. The Station must be able to accommodate such changes with a minimum disruption to operations. The changeover of obsolete subsystems will require modular designs that will allow in-service replacement without disruption of critical services.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

- Missions requirements exist which are adequate and representative for Space Station System definition.
- The initial Space Station to be developed should be a joint Research, Development and Production (RD&P)/Operations and Servicing (O&S) facility at 28.5-degree inclination/400km altitude.
- A program start in 1984 will permit a 1990 IOC for the initial Space Station. Realistically a space based OTV would not become operational before 1994.
- The mission set does not substantiate the need for a Space Station at 57-degree inclination.
- The mission set does not conclusively support the need for a Space Station in polar orbit before the year 2000.
- Operations and Servicing and Science and Applications missions can coexist on the same Space Station Facility.
- A space based OTV is a new technology vehicle providing superior performance and substantially reduced launch cost when compared to its nearest competitor.
- The Space Transportation System Shuttle can support the mission set and recommended Space Station architecture through the year 2000, assuming five orbiters are in operation and a Shuttle derived vehicle for cryogenic propellant delivery to the Space Station is developed.
- The Shuttle derived ET tanker will support OTV needs through the year 2000 with three flights per year, the ET tanker offers a low cost approach to transporting propellants to LEO.
- The propellant scavenging (Honeybee) concept studied by General Dynamics is feasible, but will not provide adequate propellants to the Space Station to support the OTV mission model established by this study.
- 96 percent of the missions set is compatible with the TDRSS. The entire mission set is compatible with TDAS.

5.2 RECOMMENDATIONS

- Continue systems analysis in greater depth with emphasis in these areas:
  - -- Power management analysis & trades
  - -- Missions environment sensitivity
  - -- Missions management analysis
- Perform preliminary design study of space station configuration options in order to accomplish the following:
  - -- Flight performance assessment
  - -- Human performance assessment
  - -- Select EC/LSS growth strategy
  - -- Verify subsystems technology needs
  - -- Substantiate growth capabilities
  - -- Verify missions compatibility
  - -- Develop integrated propellant supply & management approach
- Perform OTV System definition study as follows:
  - -- Select implement concepts
  - -- Conduct programmatics & cost analysis to determine impacts of early space based OTV deployment
- Proceed with TMS development as early as possible.
  - -- Inital Shuttle based capability first
  - -- Evolve space based versions

SECTION 6

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APPENDIX I

GLOSSARY OF TERMS

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GLOSSARY OF TERMS

Active Structural Control	A relatively new control technique which uses closed-loop operation to damp the shaking or ringing exhibited by an elastic structure when disturbed by an impulsive force.
Advanced Space Engine	An advanced O_2/H_2 engine designed for maximum vacuum performance during extended operation in space. Data use herein from a NASA contract of the same name.
Aerobraked OTV	An OTV which utilizes an aerodynamic device within the atmosphere upon its return to LEO to alter its flight path and thereby reduce its total propellant requirements for a particular mission.
Angular Coverage	The solid angle, referenced to a spacecraft coordinate system, over which an RF antenna system must operate.
Angular Momentum Exchange Device	A mechanical device which produces spacecraft control torques by means of angular momentum exchange. In its simplest form, a motor accelerates a flywheel and the reaction torque is applied to the spacecraft body so as to maintain the desired attitude.
Architecture	That set of descriptions of station elements required to accommodate the functions to be performed on the station without specifying hardware or geometrical concepts, and the system-level arrangement of those elements with respect to each other.
Attached Payload	A mission or group of missions flown on the primary station facility.
Beam Steering Algorithm	An algorithm that computes the phase and amplitude of the RF signal necessary at each element of a phased array antenna in order to point the beam in a given direction.

Bipolar Memories	Memories constructed from minority-carrier devices in which current passes across junctions of p-type (holes are carriers) and n-type (electrons are carriers) semiconductors. Examples of bipolar technologies are transistor-transistor logic (TTL), emitter-coupled logic (ECL) and integrated injection logic (IIL). Bipolar technologies are generally charcterized by fast propagation times and relatively high power consumption.
Bit Stream	A continuous series of digital bits containing information.
Bosch Process	A process for the reduction of CO_2 in which H_2 and CO_2 combine to form solid carbon and water. The reaction occurs in the range of 980 - 1,340 F in the presence of an iron catalyst. In practice, single pass efficiencies through the Bosch reactor are less that 10 percent. Complete conversion is obtained by recycling the process gases with continuous deposition of carbon and removal of water vapor. The recycled gas mixture contains CO_2, carbon monoxide (CO), water vapor and CH_4. The carbon remains in the reactor and is collected in expendable cartridges.
Bubble Memory	Memory devices which store data within "magnetic bubbles". Magnetic bubbles are miniature cylindrical magnetic domains embedded in a thin film of orthoferrite material. Magnetic bubbles can be used to achieve theoretical densities of millions of bits per square inch.
Centralized Data System	A data processing system where the processor is sufficiently large to handle all the processing requirements of the system and is located within a single system.
Communications & Tracking System Processor	A dedicated procesor that orchestrates the operation of the communications and tracking system and performs all necessary calculations for this system.
Constraint Length	Defined as K, where the number of stages in the shift register is K-1 (see Convolutional Code).
Control Moment Gyro	An angular momentum exchange device which produces control torques by means of gyroscopic precession, wherein a fixed speed rotor is rotated about an axis perpendicular to its spin axis.

Control System Management	Guiding and directing appropriate changes and/or growth of the attitude control system that are required to accommodate changes and/or growth in the physical characteristics of a Space Station.
Convolutional Coding	A method of coding a digital signal that when decoded enhances the performance of a data channel by decreasing the bit error rate. It is a sequence of transmitted signals, each of which is a linear combination of the present information bit and the previous K-1 information bits. These codes can easily be generated by a shift register.
Core Elements	Permanent central elements of the Space Station which provide the basic utilities and resources required to accommodate missions and operations performed on the Space Station.
Data Bus	A data bus is the medium by which information is transferred between resident devices (computer, controllers, terminals, etc.) in a system. Data buses are generally manufactured from wire (twisted shielded pairs, coaxial cables, etc.) or fiber optics (glass, plastic, etc.).
Detached Payload	A mission or group of missions flown apart from the primary station facility.
Dewar Tank	A double walled vacuum enshrouded cryogenic propellant tank which reduces thermal leakage and therefore boiloff to an absolute minimum.
Distributed Data System	Definitions of a distributed data system are varied. Here are three common definitions: (a) Processing load is shared by a number of processing elements. (b) A collection of processing elements interconnected logically and physically. (c) System-wide operating system so that the distributed nature is transparent to the user and the computer functions are dispersed among several physical computing elements.
Earth Pointing	An Earth-oriented frame of reference maintained by a spacecraft in order to observe the Earth.

Electrochemical Depolarized Concentrator (EDC)	The EDC is an electrochemical method that continuously removes CO_2 from a flowing air stream and concentrates the CO_2 to a level useful for O_2 recovery. The CO_2 removal takes place in an electrochemical module consisting of series of cells. Each cell consists of two electrodes separated by a matrix containing an aqueous carbonate electrolyte. Plates adjacent to the electrodes provide passageways for distribution of gases and electrical current. Two moles of CO_2 are theoretically transferred for one mole of O_2 consumed. This ratio represents the process efficiency, and 100 percent efficiency occurs when 2.75 g of CO_2 is transferred for each g of O_2 consumed. The electrical power produced by the EDC can be directly utilized by the Oxygen Generated Subsystem.
Ephemeris	The computed position versus time of a celestial body.
Ephemeris Data	Data from which the computation of an ephemeris is performed.
ET Tanker	A particular concept for delivering O_2/H_2 propellant to orbit with a Shuttle Derived Vehicle that features a propulsion module instead of the entire STS orbiter. Cryogenic propellant is carried within the ET itself instead of in separate tanks.
Expendable OTV	An OTV which is not reused after a particular mission due to high payload energy requirements which preclude its return to LEO.
Expendable Upper Stage	An upper stage to a launch vehicle, such as Centaur or IUS, which is not recovered for reuse after it has delivered a payload to its mission orbit.
Free Flyer	Any space facility not attached to a space station.
Function	The purpose for which a system, subsystem or element thereof is designed or exists.
General Purpose Module	A pressurized module designed to serve as the core module of a space station containing emergency provisions and equipment which would allow it to serve as a Safe Haven. It also contains all of the major utilities interfaces, as well as the basic subsystems required to control and operate the space station.

Habitat Module	A pressurized enclosure designed to provide primary crew living quarters including food preparation, sleep, and recreational facilities, and essential environmental control and life support systems.
High Density Digital Magnetic Tape Recorder	A magnetic tape recorder which achieves high density capabilities by using a wide high quality recording medium. As many as 52 heads have been used on a one inch wide tape to achieve 300 M bits storage on a 14 inch reel.
High Level Modules	Self-contained autonomous core function computer systems which are loosely coupled to a main bus.
High Speed Multiplexer	A multiplexer operating at speeds of tens to hundreds of megabits per second.
Honeybee Concept	A particular concept for recovering residuals from the External Tank which utilizes the OTV to accelerate the ET and extract H_2 and O_2.
Housekeeping	The set of tasks performed by the crew required for the daily maintenance, upkeep, and cleaning of a manned facility.
Inertial Pointing	An Inertially-oriented frame of reference maintained by a spacecraft in order to observe deep space objects.
Integrated Control Torque Commands	The time integral of the signals from the control electronics which command torques from the torque-producing devices such as control moment gyros.
K-Band	The RF frequency spectrum between 10.9 and 36.0 GHz. Ku-Band is that portion of the K-Band between 15.35 and 17.25 GHz.
Level I Maintenance	Maintenance that occurs on the vehicle.
Level II Maintenance	The repair, or attempted repair, at the Space Station of units that have been removed from the vehicle.
Level III Maintenance	Maintenance activities on units that have been returned to earth for disposition.
Logistics Module	A pressurized module designed for the storage of a 90-day consumables and equipment supply for all or part of the station crew and missions.

Low Bandwidth Attitude System	The bandwidth of an attitude control system is that frequency above which sinusoidal disturbances are essentially ignored and below which sinusoidal disturbances are controlled. In a very low bandwidth system, the higher frequencies are filtered out, stability is less of a problem, and control component requirements are more relaxed. However, the pointing is not as accurate and the response is not as fast as with a high bandwidth system.
Man Interaction	Human involvement in the operation of a mission.
Man Operated	A requirement for the presence of a human to facilitate the operation of a mission or payload.
Man Tended	A requirement for man's presence during occasional on-orbit servicing of a mission or payload.
Membrane Processes	When referring to water reclamation, these processes include Reverse Osmosis (Hyperfiltration) and Electrodialysis. Reverse Osmosis (RO) refers to the process of pressure-driven separation of water and contaminants employing a semipermeable membrane barrier. The purpose of the membrane barrier is to reject suspended and dissolved solids while water selectively permeates the membrane. In general, the membrane(s) will effectively reject ionic species and large organic molecules, but small organic molecules (i.e., urea) and non-ionized acids and bases will be poorly rejected. Thus, hyprochlorite oxidation of ammonia and urea is used for post-treatment of RO product water.
Missions Module	A pressurized module designed to accommodate missions on board the Space Station.
Mission Requirements	The physical and performance capabilities required of a spacecraft or space station in order to support the objectives of a mission.
Mission Set	The total spectrum of space missions proposed or planned for the 1990 through 2000 time period.
Modal Oscillations	The vibrations, shaking, or ringing of an elastic structure when disturbed by an impulsive force such as docking impact.
Multi-beam Steerable Phased Array Antenna	A phased array antenna with more than one main beam, each of which is steerable by means of adjusting the phase and amplitude of each of the RF signals from each element of the array.

Multi-mission Platforms	Free flying orbital facilities which accommodate more than one mission at a time.
Multiple Access	Designation of a group of TDRSS S-Band data channels that share a common RF frequency and TDRS antenna. Up to 20 users can be supported simultaneously. Code division multiple access is used to differentiate between the various channels.
Multiplexer	A device that generates a bit stream of data from more than one source of input data.
Non-stringent Pointing	An attitude control system requirement to hold spacecraft attitude within one or two degrees of nominal. This requirement corresponds to the performance of a low bandwidth attitude control system.
Non-Volatile RAM	Random Access Memory which retains its programmed data after power has been removed and is reapplied.
Null Steering	The positioning or steering of an antenna pattern such that antenna pattern nulls are pointed at sources of RF interference while maintaining communications with desired targets.
Omnidirectional Coverage	Angular cover of 4 steradians.
Operational Floor Plan	A diagrammatic layout showing the relative location of work areas and equipment within a facility.
Operational Memory	That portion of the memory of a computational system that is immediately available for use by the central processor.
Operations Management	Planning, directing, monitoring and control of the manned and unmanned operations of a space station.
Optical Disk	A rapid access disk memory which reads and writes data on a special surface using optical techniques (lasers). The benefits are the data density (capacities of up to 100 B bytes on a 14 in. disk have been reported) and the relatively long distance between the sensor and the disk surface. Presently, erase technologies are immature but promise to advance. This will remove the major drawback of the device.
OTV	Orbital Transfer Vehicle; a reusable propulsive system used to ferry payload from one orbit to another.

OTV Base	A space station equipped to maintain, assemble, service repair and integrate Orbital Transfer Vehicles and their payloads.
Payload	Cargo carried by the Shuttle, OTV, or TMS. Also the instruments, sensors, functional hardware, and controls needed to perform a particular mission when operated by a spacecraft or space station.
Payload Capture Ratio	The fraction of the total payload delivery market which a particular launch vehicle may be expected to 'capture' from competing systems.
Platform	An unmanned spacecraft capable of accommodating multiple payloads.
Platform Guidance System	A guidance system containing gyros that remain fixed inertially in space. Vehicle attitude is obtained by noting the relative angular pointing of the reference gyros and the vehicle coordinate axes.
Power Management	The generation, distribution, conservation, monitoring and control of a spacecraft or space station subsystem.
Quadraphase Modulated Signal	A method of phase modulation of an RF signal whereby the phase of the signal can assume one of 4 possible states differing in phase by multiples of 90 degrees.
Quadrature Channel	The Q-channel in the TDRSS. This is one of the two data channels (the other is the I-channel) used for quadraphase modulation of the RF carrier.
Robotic	Autonomously controlled without human interaction.
Sabatier Process	A process for the reduction of CO_2 which is ideally suited for an air revitalization system that uses a hydrazine-based N_2 generation subsystem. CO_2 and H_2 enter the Sabatier reactor and are converted to methane (CH_4) and water. The reaction occurs around 700 F and is aided by a catalyst. The water is condensed in a liquid cooled porous plaque condenser/separator. The exhaust gases, primarily CH_4, are vented overboard. Single pass high conversion efficiency (98-99 percent) subsystems have been developed.

Safe Haven:	A location within the Space Station which provides an environment safe from hazards such as Solar Flares and explosive decompression in the station. It also provides consumables for the crew which enable them to survive until rescued.
Satellite Servicing	Maintenance, replenishment of consumables, refurbishment or repair of a spacecraft and/or its payload.
S-Band	The RF portion of the spectrum between 1.55 and 5.20 GHz.
Scar	Unused electrical and mechanical parts or mounting interfaces provided on existing equipment which allow for future installation of new hardware.
Scavenging	The process of recovering fluids which would otherwise not be utilized on orbit. Used especialy in the context of recovering residual cryogens from the ET after MECO.
Service	The replenishment or replacement of consumables required by an orbital spacecraft or space launch vehicle.
Shuttle Tended	A satellite serviced, repaired, or reconfigured directly by the Shuttle rather than by the Space Station.
Simple Active Damping	Active structural control which does not require a digital computer to implement a multiple input-multiple output control law.
Simple Rigid Body State Estimator	A control technique to estimate the angular rate of a conceptually undeformed elastic spacecraft. Angular rate is required for stability and any single sensor on an elastic body will sense the elastic motions as well as the average motion of the entire body.
Single Access	Designation of one or two TDRSS data channels, either in S-Band or K-Band, on each of the TDRSS that are dedicated to serving one user at a time. Data rates capabilities are higher than the multiple access channels. Each single access channel has its dedicated TDRS high gain antenna and dedicated RF frequency.
Solar Pointing	A Solar-oriented frame of reference maintained by a spacecraft in order to observe the sun.

South Atlantic Anomaly	That portion of Earth's Inner Radiation Belt centered at 35 degree West Longitude, 35 degree South Latitude which dips to within 400-500 KM of the Earth's surface.
Space Facility	A manned or unmanned spacecraft or space station.
Spacecraft:	A bus which contains all of the essential utilities, flight controls, and structural characteristics required for on-orbit operation of a payload.
Spacecraft Placement	Insertion of a spacecraft into its operational orbit.
Spacecraft Retrieval	Removal of a spacecraft from operational orbit by returning it to the Space Station or to Earth.
Space Station	A permanently manned space facility which supports missions that require long duration operation by humans, periodic servicing and maintenance, or space based transportation systems.
Space Station Missions	Missions which propose to be accommodated by the Space Station.
Space System	The entire earth orbital space infrastructure required to accommodate a mission set.
Spread Spectrum	A method of modulation of an RF signal that increases the bandwidth of the modulated signal many times over the bandwidth of the information signal.
Structural Rotational Rate	The first derivative of the instantaneous angle between a small element of shaking or ringing elastic structure and the position of that element when the structure is not shaking or ringing.
Synchronous Satellite	A satellite placed in an equitorial orbit of approximately 19,450 NM where the orbital period is equal to the period of rotation of the earth. The satellite thus appears stationary over one point on the surface of the earth.
Teleoperator Maneuvering System	A modest capability orbital transfer vehicle equipped to perform servicing and maintenance tasks on satellites while being remotely controlled by a human operator.

Terminal Modules — Subsystem processors which, depending on the function to be accomplished, could work autonomously or in conjunction with a high level module.

Tethered Spacecraft — An auxiliary spacecraft attached to a primary spacecraft by means of a mechanical tether which may also serve as a conduit for the transfer of electrical signals between the spacecraft.

Thermal Bus — A network of thermal conductors and conduits for collecting waste heat from distributed subsystems and conveying it to a disposal device.

Thermal Management — The collection, transport, disposal, monitoring and control of the waste heat generated by a spacecraft or space station.

Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES) — A process for reclamation of water in which pretreated waste water (urine) undergoes a sequence of evaporation under reduced pressure and then condensation. The pretreated waste water is heated to approximately 150 degrees F in a thermoelectric heat exchanger, and the heated waste water is pumped through a hollow fiber polysulfone membrane evaporator module. The exterior of the module tubes is exposed to reduced pressure, and water evaporates from the tube surface and is condensed on a chilled porous plate surface in thermal contact with the cold junction surfaces of the thermoelectric heat exchanger. The heat of vaporization is provided by recycling the waste water to the heat exchanger where it is reheated and recycled. The product water from this subsystem concept requires the same post-treatment steps as those used by the VCD process. The energy requirements for this process are primarily for the thermoelectric heat pump and for the subsystem pumps (recycle, cooling, and condensate).

Tracking & Data Acquisition System (TDAS) — The next generation of the TDRSS, planned to be operational in the early 1990's, that will have enhanced data handling capability.

Tracking & Data Relay Satellite System (TDRSS) — A NASA system consisting of two synchronous satellites (and a spare) and a ground network developed for the purpose of transmitting data to and from low altitude spacecraft.

Vapor Compression Distillation (VCD)	A process for reclamation of water in which pretreated waste water (urine) undergoes a sequence of evaporation, compression, and condensation. By compressing the vapor to raise its saturation temperature and then condensing the vapor on a surface which is in thermal contact with the evaporator, latent heat is recovered. The resultant heat flux from the condensor to the evaporator is sufficient to evaporate an equal mass of water. Thus, the latent heat of condensation is recovered for the evaporation process, and the only energy required by the process is that necessary to compress the vapor and to overcome the thermal and mechanical inefficiencies. Post-treatment in charcoal and ion exchange beds, and the addition of biocide is required to achieve potable water standards.
Vapor Phase Catalytic Ammonia Removal	A process for reclamation of water which requires neither pretreatment nor post-treatment. In this process waste water (urine) is vaporized, and the vapor stream is mixed with air or O_2 and passes through an oxidation reactor. Ammonia, urea and light organics are oxidized in this reactor. Water is condensed and separated, and the vapor phase then passes through a nitrous oxide (N_2O) decomposition reactor which converts the N_2O to N_2 and O_2. Regenerative Heat Exchangers are required by this process in order to recoup the latent heat of condensation (as in the VCD and TIMES) and to recoup the heat in the vapor phase catalytic reactors.
Video Data Compression	A method of processing the information contained in a video signal that reduces the bandwidth required to transmit the signal.
W-Band	The RF frequency spectrum between 56.0 and 100.0 GHz.
Zone-of-exclusion	A zone extending from the surface of the earth to an altitude of 1200 KM and centered over the Indian Ocean in which no communication with the TDRSS is possible due to the geometrical placement of the two TDRS spacecraft.

APPENDIX II

SERVICING MISSIONS TO OTHER INCLINATIONS

APPENDIX II

SERVICING MISSIONS TO OTHER INCLINATIONS

The Space Station has a substantial economic advantage over the Space Shuttle in the servicing of: 1) assets in low Earth-orbit within range of the Space Station TMS, and 2) assets in high orbits beyond the Shuttle's servicing range. For certain missions beyond the range of the Space Station TMS, and within range of the Shuttle, however, the Shuttle could remain the most cost-effective means for servicing. This will be a factor primarily in the servicing of 57-degree orbit LEO free-flyers and/or platforms. Servicing of these facilities from the Space Station would require use of the OTV, at an estimated cost of $19.3 million per mission. The cost of utilizing the Shuttle for the same type of mission would be $17.1 million. The derivation of these cost estimates is shown in Table II-1.

Table II-1. Cost of Servicing 57-Degree LEO Assets from Space Station vs. Space Shuttle

	Space Station	Space Shuttle
STS Cost	$ 5.6 M	$17.1 M
OTV Cost	13.7 M	N/A
TOTAL	$19.3 M	$17.1 M

Servicing from the Space Shuttle requires a considerable STS cost, since commonly-used servicing equipment must be launched to orbit via STS for every servicing mission. Space Shuttle servicing also requires use of the TMS, resulting in a total STS cost much higher than if use of this 7500-pound stage were not required. The TMS would be used in conjunction with a Versatile Servicing Stage (VSS), which would add another 1500 pounds to the STS launch requirement. The total STS charge also includes deliverly of 1000 pounds of mission-peculiar consumables.

The STS cost is much lower when the Space Station is used as a base for servicing. Only the mission-peculiar consumables need to be delivered via Shuttle, resulting in the minimum $5.6 million STS charge, based on use of 1/20th or less of the Shuttle's capacity. Since the servicing mission is beyond the range of the Space Station TMS, however, the space-based OTV must be used for delivery of the VSS and consumables to the serviced asset. The cost of this OTV mission ($13.7 million, including $4 million in operations and $9.7 million for 19,400 pounds of OTV propellant delivered to LEO at $500/lb), however, offsets the reduction in STS cost, and results in a higher overall mission cost than for servicing from the Shuttle.

The cost of servicing from the Space Station could be reduced by nearly $4 million, if the cost of deliverying consumables to the Space Station via STS could be reduced below the current $5.6 million minimum Shuttle charge. This could be accomplished by a change in STS pricing policy, or by sharing of the allotted 1/20th of cargo bay capacity among multiple users. If the volume of the required consumables were sufficiently small, then consumables for up to three servicing missions could be delivered to LEO for the same $5.6 million STS charge. In this case, servicing from the Space Station would in fact become less expensive than Shuttle servicing, although by a margin of less than ten percent. It can therefore be concluded from this assessment only that servicing costs from the Shuttle and Space Station for these types of assets will be very similar.